NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3590

INVESTIGATION OF FAR NOISE FIELD OF JETS

I - EFFECT OF NOZZLE SHAPE

By Edmund E. Callaghan and Willard D. Coles

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Cleveland, Ohio

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3838

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SUMMARY

An investigation of the effect of nozzle shape on the noise generation of air jets was conducted on convergent (circular, square, rectangular, and elliptical), convergent-divergent, and several plug-type nozzles. The nozzle areas were approximately equal to the area of a 3- or 4-inch-diameter circular nozzle. At jet pressure ratios less than 2.2, all the nozzles had essentially the same sound field. At higher pressure ratios, only the convergent-divergent nozzle showed any appreciable reduction in sound power below that of an ordinary convergent nozzle. All nozzles showed discrete-frequency-type noises at high pressure ratios. The convergent-divergent nozzle eliminated such discrete frequencies when operated near its design point.

CC-1

INTRODUCTION

The sound field generated by the discharge of a circular jet into the surrounding atmosphere has been the subject of considerable research (refs. 1 to 5). As yet, however, the effect of nozzle shape, other than modifications of basically circular nozzles, on noise generation has not been extensively investigated. There is reason to believe that nozzle shape (cross-sectional shape and/or longitudinal contour) may affect noise generation, particularly at high jet pressure ratios. Results reported to date show that the sound field generated by a jet is associated with the jet flow field. In general, there are two separate flow regimes for a jet issuing from a convergent nozzle. At low jet total- to static-pressure ratios (less than 2.2), the flow is subsonic or transonic, and the sound generation is caused by the turbulent mixing of the jet with the surrounding atmosphere. As might be expected, the sound-field spectrum generated by such a process is more or less random in nature and is relatively free from discrete frequencies. At high jet pressure ratios the jet is overchoked, and the jet static pressure, after leaving the nozzle, is greater than the surrounding atmosphere, thus resulting in strong shock-wave formations. In this case, the sound spectra have discrete frequencies of greater amplitude imposed on the mixing noise. The sound power in these discrete frequencies is usually sufficiently high to override the turbulent mixing noise.

The mechanism of jet-noise generation by either turbulent mixing or shock waves is not completely understood at present. Lighthill analyzed theoretically the sound field resulting from a region of turbulence located in a uniform acoustic medium (ref. 6). Although the final result of this theory has been successfully applied to jet-noise generation, as yet there has been no experimental evaluation of the detailed processes used in the analysis. Lighthill predicted the variation but not the magnitude of sound-power[1] generation with conditions of the jet and the surrounding medium (ref. 6). His predictions are verified by experiment, and to a first approximation, it appears that changes in nozzle shape would not greatly alter the mixing process downstream of the nozzle. Consequently, no large changes in the sound field are expected at low pressure ratios. 3838

Reference 5 suggests that the mechanism causing the discrete frequencies in overchoked flows depends on a regular stream disturbance traversing the shock pattern in the jet. This action is of a self-propagating nature, as described in reference 5, and the frequency of the emission depends on the diameter of the jet and the spacing of the shock waves. This process is not particularly stable and is affected by minor variations in jet conditions. It would appear, therefore, that changes in nozzle shape would alter the sound generation mechanism. In fact, by proper design of either convergent-divergent or plug-type nozzles, high-pressure-ratio operation should be achieved without shock waves and hence discrete frequencies.

This investigation, concerned with the effect of nozzle shape on jet-noise generation, was conducted at the NACA Lewis laboratory and represents a portion of a study of jet noise and means for its suppression. The discussion of the data in this report is divided into sections on the low-pressure-ratio design convergent nozzles (circular, square, rectangular, and elliptical) and the high-pressure-ratio design nozzles (convergent-divergent and plug nozzles designed for shock-free expansion of the jet to supersonic velocities).

APPARATUS AND PROCEDURE

A schematic diagram showing the piping layout for the air supply to the air jet is shown in figure 1. Air is supplied at either 40- or

[1]The nomenclature of acoustic terms (sound pressure, sound pressure level, sound power, and spectrum level) used in this report is that of reference 7.

125-pounds-per-square-inch-gage pressure from compressors situated at a considerable distance from the experimental setup. Moisture separation equipment is included in the air-supply system; but to eliminate condensation effects at the nozzles, the air was heated to approximately 200° F in the large gas-fired heat exchanger (fig. 1). The air jet was located to provide a sound field free of buildings and other reflecting surfaces. The nearest reflecting surface downstream of the air jet was a low building 190 feet distant. At the sides, the nearest building was 280 feet away, and the building housing the control room and heat exchanger was 125 feet upstream of the air jet. A photograph of the plenum chamber with a nozzle installed is shown in figure 2.

In order to ensure that the generation of the extraneous noise from the piping and associated equipment would be kept to a minimum, the following precautions were taken:

(1) The pressure control valve was of a design having low noise-level characteristics and was located inside the building approximately 175 feet from the air jet.

(2) The flow-measuring orifice was located approximately 150 feet from the jet.

(3) Two mufflers were provided downstream of the last bend in the line.

(4) A diffuser section equipped with screens was used to prevent flow separation and provide a uniform velocity profile at the plenum inlet.

(5) The large plenum was used to provide low air velocity upstream of the nozzle.

(6) A smooth bellmouth entry to the nozzles was provided.

The total pressure and temperature of the air were measured at the plenum chamber. In general, the controls used on the throttling valve and the air heater allowed pressure and temperature deviations to be kept within ±0.1 inch of mercury and ±10° F, respectively, of the prescribed setting.

Seven convergent nozzles, a convergent-divergent nozzle, and two types of plug nozzles were investigated. Three of the convergent nozzles were 60° conical nozzles of 3-, 4-, and 5-inch-diameter throats. The other convergent nozzles were of square, rectangular, and elliptical cross sections (fig. 3) and had throat areas equal to the area of the 4-inch-diameter conical nozzle. The two elliptical nozzles had axis ratios of 2 and 4. The convergent-divergent nozzle (fig. 4(a)) had a

4-inch-diameter throat and a design pressure ratio of 3.0. Two types of plug nozzles are shown in figures 4(b) to (e). One type had conical plugs, and the other type had plugs giving approximately isentropic expansion of the jet. Nozzles of each type having design pressure ratios of 4.0 and 9.5 were used.

Sound measurements were taken at radial distances of 25, 50, and 100 feet from the jet (fig. 1). Measuring stations were located at 15° increments of azimuth over the range from 120° from the jet axis on one side to 90° from the jet axis on the other. The plenum chamber and nozzle assembly were 10 feet above the ground plane, and all the sound measurements, except the frequency measurements, were made at that height. The frequency-distribution data were made approximately 6 feet above ground level at a distance of 50 feet. 3838

Sound-pressure-level data were obtained using "C" weighting on a General Radio Company Type 1551-A Sound-Level Meter with dynamic microphone and are based on a reference level of 0.0002 dyne/cm^2. The sound-spectrum data were obtained using a Brüel and Kjaer Audio Frequency Spectrum Recorder Type 2311 having a frequency range of 35 to 18,000 cps and a Condenser Microphone Type 4111. The frequency range is divided into 27 bands of 1/3-octave width. The microphone meter systems of both instruments were calibrated prior to each period of operation with a General Radio Company Type 1552-A Sound-Level Calibrator and a Type 1307-A Transistor Oscillator.

The following procedure was used for each nozzle configuration: Air-jet pressure conditions were established in pressure increments of 4 inches of mercury in ascending order, since preliminary tests showed no effect of ascending or descending pressures. Sound-level surveys were made at each value of jet total pressure over a range of plenum-chamber- to ambient-pressure ratios from approximately 1.45 to 3.25 for the low-pressure design nozzles and 1.45 to 4.2 for the high-pressure design nozzles.

Although extreme care was taken to calibrate the sound-measuring equipment, other sources of error affected the results. Because the jets are small, the wind has a considerable effect on the jet direction. No tests were made at wind velocities greater than 10 mph, but some errors do occur because of wind gusts. Tests made on different days with the same nozzle showed that local sound-pressure-level variations might be as high as ±3 decibels. However, the sound-power levels always varied less than ±1 decibel. The sound power should be expected to have less error since it results from an integration over the whole sound field, and errors in local values would tend to average out.

A small error in the total acoustic power resulted because no sound-pressure measurements were made upstream of 120° from the jet axis. This error was quite small, since the sound-pressure levels in this area were always 10 decibels or more below the maximum value and contributed very little to the total acoustic power.

RESULTS AND DISCUSSION

3838

Total Acoustic Power

The total acoustic power radiated by a jet can be calculated from the measured sound-pressure levels by the procedure described in reference 8. The essential assumptions for these calculations are as follows: symmetry of the sound field about the jet axis, the ground plane acting as a perfect reflector, and a sufficiently large distance from the effective source to the observer, so that the sound waves are essentially plane waves. Much of the sound-power data contained herein is presented in watts. For purposes of convenience, reference is also occasionally made to sound power in decibels (based on a reference power of 1×10^{-13} watts).

Convergent nozzles. - The sound power radiated by circular convergent nozzles (3-, 4-, and 5-in. diam) as a function of jet pressure ratio is shown in figure 5. (The jet pressure ratio, as used in this report, is the ratio of the plenum-chamber total pressure to the atmospheric pressure.) As expected, there are separate curves for each nozzle diameter. Data at high pressure ratio for the 5-inch-diameter nozzle were not taken because of air-supply limitations. Figure 5 shows at least two distinctly different curves for each nozzle, dependent on the pressure ratio. Above a pressure ratio of 2.1, there is a distinct increase in the sound power with pressure ratio. This increase in the rate of sound output results from shock-wave formations in the jet (ref. 5). At pressure ratios above 2.6, the curves show a tendency to flatten up to a pressure ratio of about 2.9, above which the sound power for the 3-inch-diameter jet again shows a marked tendency to increase. The other nozzles might also have shown similar increases at the higher pressure ratios.

Lighthill predicted a linear variation of radiated sound power with jet-nozzle area (ref. 6). This prediction is verified in figure 6, a plot of total-sound-power to nozzle-area ratio as a function of jet pressure ratio for the three circular nozzles. Although Lighthill's theory only applies to pressure ratios less then choking (1.89), the data for the three nozzles fall along a single curve for the whole range of pressure ratios investigated. The data for figures 5 and 6 at pressure ratios less than 1.89 are shown in figure 7 in terms of the Lighthill sound-generation parameter

$$\rho_0 A V^8 / a_0^5$$

where

ρ_0 ambient air density, slugs/cu ft

A nozzle-exit area, sq ft

V jet velocity, ft/sec

a_0 ambient acoustic velocity, ft/sec

3838

In this figure, the total sound power is plotted as a function of the Lighthill parameter, both in watts. The good correlation is expected from the good subsonic correlation of figure 6. The Lighthill parameter and pressure ratio are directly related for these tests, since the atmospheric conditions and jet total temperature are essentially constant. Hence, ρ_0 and a_0 are nearly constant. Since V is related directly to pressure ratio at constant total temperature, the good correlation of figure 7 follows naturally from figure 6. In addition, a line of unity slope (fig. 7) drawn through the data points verifies the prediction of Lighthill. It is interesting to note that the free-field measurements of figure 7 agree well with the reverbrant chamber data of reference 3.

The effect of nozzle shape on the sound power generated is shown in figure 8 as a plot of sound-power to nozzle-area ratio as a function of jet pressure ratio for the circular (3- and 4-in. diam), square, rectangular, and elliptical nozzle-exit shapes. In general, nozzle-exit shape does not have much effect on sound-power generation. The spread in the data for pressure ratios less than 2.2 amounts to only a 3-decibel variation in sound power. There is a tendency for most of the data to fall below that for the circular nozzle. This is particularly true for the pressure ratios between choking (1.89) and 2.6 and is believed to result from the asymmetric nozzle shapes, which would alleviate the discrete-frequency-sound generation described in reference 5.

Convergent-divergent and plug nozzles. - Shock waves in the jet materially increase the sound power radiated by the jet. The convergent-divergent and plug-type nozzles used in this investigation were designed to provide shock-free flow at a particular pressure ratio. The design pressure ratio of the convergent-divergent nozzle was 3.0. Figure 9 shows the sound-power to nozzle-area ratio as a function of pressure ratio for this nozzle. Also shown on the figure are the convergent-nozzle data of figure 6 and a curve corresponding to a V^8 relation of sound power to velocity. For this curve, the velocity was calculated for fully expanded isentropic flow from the pressure ratio and jet total temperature (200° F). The data for the convergent-divergent nozzle fall slightly below the convergent-nozzle curve at the low pressure ratios, because the exit velocity from a convergent-divergent nozzle is lower than that for a convergent nozzle at any plenum-chamber total- to atmospheric-pressure ratio less than 1.87. For this particular nozzle, the throat diameter was 4.0 inches and the exit diameter 4.12 inches. For this geometry, the throat chokes at a plenum total- to atmospheric-pressure ratio of 1.46, and the flow downstream of the throat diffuses to a lower exit velocity than for the convergent nozzle.

3838 The data for the convergent-divergent nozzle cross the V^8 curve at a pressure ratio of about 2.05 and continue upward until a sound-power peak is obtained at a pressure ratio near 2.6 (fig. 9). As the pressure ratio is increased, the sound power decreases to a minimum at a pressure ratio of 2.9. Although the general trends in the data for the convergent and convergent-divergent nozzles are somewhat similar, the decrease in sound pressure at a pressure ratio near 2.9 is much more marked for the convergent-divergent nozzle, and the sound power radiated is only one-third to one-half as much. The sound-power decrease from a pressure ratio of 2.4 to a minimum at 2.9 is of considerable interest. Decreasing the shock strength results in substantial decreases in the sound-power generation. The minimum occurs at 2.9 rather than at the design value of 3.0, because the boundary-layer buildup inside the nozzle reduces the effective area of the exit.

Figure 10 shows the sound-power to exit-area ratio as a function of jet pressure ratio for all the plug nozzles investigated. Also shown on the figure is the V^8 curve of figure 9. Neither of the nozzles with a design pressure ratio of 4.0 shows any real tendency toward decreased sound power at or near design pressure ratio, as was shown for the convergent-divergent nozzle (fig. 9). The nozzles with a design pressure ratio of 9.5 follow closely the data for the nozzles with a design pressure ratio of 4.0 over the whole range of pressure ratios investigated, with the exception of a sharply decreased sound power which occurred near a pressure ratio of 3.2 for the isentropic (9.5) plug nozzle. This decrease resulted from sudden cessation of the usual resonance or squeal associated with nozzle operation at high pressure ratios. The reasons for the decrease were not investigated with flow-visualization equipment, but they would probably become apparent from such a study. None of the nozzles showed the consistent trend toward lower noise levels evidenced by the convergent-divergent nozzle (fig. 9).

Sound Spectra

Sound spectral measurements of all the nozzles were used to further evaluate the effects of nozzle shape and jet pressure ratio on the sound-generating characteristics of the nozzles. The rather wide spread frequently encountered in the spectral data at the low frequencies results from wind noise. Data below 200 cps are greatly affected by the wind, but less than 2 percent of the total energy in the entire spectrum lies below 200 cps. This will be shown later in the report.

Convergent nozzles. - The sound spectra of the 3-inch-diameter nozzle at a 50-foot radius and azimuths of 30° and 90° are shown in figure 11 for a wide range of pressure ratios. At both the 30° and 90° positions there is considerable similarity in the general shape of the spectra at the low pressure ratios (less than 2.2). At the higher pressure ratios the spectra show sharp peaks indicative of resonance-type noises. This is particularly evident at the 90° position. At a pressure ratio of 2.55 there is a sharp peak at 4000 cps, and at a 4.15 pressure ratio peaks occur at 1600 and 3200 cps. 3838

The effect of nozzle diameter on the sound spectra is shown in figure 12. As would be expected, the spectrum level increases with increasing diameter (fig. 12(a)). However, there is also a tendency for the energy to shift to higher frequencies with decreasing diameter. This is clearly illustrated in figure 12(b), a plot of the cumulative sound intensity (total intensity below a given frequency) as a function of frequency. These results are typical of all the circular-nozzle data, regardless of pressure ratio or measuring position.

Figure 13 shows the effect of nozzle shape on the sound spectra. All the nozzles shown in this figure have an exit area equivalent to the 4-inch-diameter circular nozzle. For all the data, the shapes of the spectra are essentially independent of nozzle shape or position. This is particularly true at low pressure ratios and a 90°-azimuth position (fig. 13(c)), where the spread of the data is of the same order as the wind error. At the same position, but a higher pressure ratio (fig. 13(d)), all the data except the 4:1 elliptical nozzle in the vertical position are in good agreement. The data for the 4:1 ellipse in the vertical position show a tendency for a shift in energy to the higher frequencies for all the pressure ratios and positions. This shift to the higher frequencies is, as might be expected, due to the decreased effective nozzle dimension in the plane of the sound measurements.

The spectrum distribution of the total sound power radiated by the 4-inch-diameter circular nozzle at pressure ratios of 1.85 and 2.55 is shown in figure 14. These results were calculated from spectrum measurements made at all the 50-foot-radius positions. The sound pressures in each 1/3-octave band were integrated in the same manner as the over-all sound pressures (to obtain total sound power). Sound energy increases quite rapidly above 200 cps (fig. 14). At the higher pressure ratio, a small peak in the frequency-distribution curve occurs at 1600 cps. The cumulative sound power (total sound power below a given frequency) for these data is shown in figure 15. Less than 2 percent of the sound energy lies below 200 cps, and more than 90 percent of the sound energy lies between 200 and 4000 cps.

Convergent-divergent and plug nozzles. - The sound spectra of the convergent-divergent nozzle for a wide range of pressure ratios is shown in figure 16. The large peak in the spectrum at 2500 cps and a pressure ratio of 2.27 disappears as the pressure ratio is increased to near the design value. The reduction in sound power (fig. 9) is due to the elimination of such noise.

The spectra for the four plug nozzles for a range of pressure ratios at the 30° and 90° azimuths (50-ft rad) are shown in figure 17. The shapes of the spectra at the 90° azimuth are quite similar except for the existence of discrete frequencies at the highest pressure ratio. Strong peaks exist at 1200 and 2500 cps for the conical plug nozzle with a design pressure ratio of 4.0 (fig. 17(e)) and the isentropic plug nozzle with a design pressure ratio of 9.5 (fig. 17(h)). Again at the 30° position, the spectra are quite similar except for a single peak at a pressure ratio of 4.15 for the isentropic plug nozzle with a design pressure ratio of 9.5 (fig. 17(d)).

3838

Directional Effects

The directional characteristics of the noise are an important parameter in specifying the effect of a change in the sound generation. Conceivably, directional changes might be more significant in a particular case than changes in sound power or maximum sound level.

CC-2

Convergent nozzles. - The effect of jet pressure ratio on the directional characteristics of a jet is illustrated by the sound polar diagram of figure 18. The results shown were obtained with the 4-inch-diameter circular convergent nozzle and are typical of those obtained with the various nozzle-exit shapes. At low pressure ratios, the maximum sound-pressure level occurs at about 30° off the jet axis with the minimum occurring forward at 120° from the jet axis. At the high pressure ratios, the maximum still occurs at the 30° position, but a second peak occurs near the 90° position, and the minimum value at either 75° or 120°.

A comparison of the different nozzle-exit shapes at several pressure ratios is shown by the sound polar diagram of figure 19. At the low pressure ratio (fig. 19(a)), there is practically no effect of nozzle shape on the directional pattern, although the circular and square nozzles have slightly greater values than the other nozzles.

At the high pressure ratio (fig. 19(b)), there are no large differences in the sound polars. The circular nozzle has a slightly higher sound level than the other nozzle shapes. This is particularly evident at the 90° off-axis position. As mentioned previously, the slightly lower values obtained with the noncircular-nozzle shapes may result from the asymmetry of the shock pattern. This asymmetry would reduce the discrete frequencies resulting from the regularity of the shock pattern as described in reference 5.

Convergent-divergent and plug nozzles. - The sound polar diagrams for the convergent-divergent nozzle for a range of pressure ratios are shown in figure 20. At the low pressure ratios, the results are quite similar to those of the circular convergent nozzle (fig. 18). At the higher pressure ratios, the convergent-divergent nozzle does not show the secondary peak at 90° and 270° exhibited by the ordinary circular convergent nozzle (fig. 18). This effect, combined with slight changes over the entire sound field, results in reduced sound power as compared with a convergent nozzle.

3838

The sound polar diagrams for all the plug nozzles for a range of pressure ratios are shown in figure 21. All these data are similar to the results obtained with the convergent nozzles. At both low and high pressure ratios, the curves are similar in shape but at a slightly different level, dependent on the jet area.

SUMMARY OF RESULTS

As part of a program for studying jet noise and means for its suppression, different kinds of nozzles have been investigated and the following results obtained:

1. At low jet pressure ratios (less than 2.2), the nozzle-exit shapes investigated had a negligible effect on the sound field (sound power, spectra, and direction) radiated by a jet.

2. At high jet pressure ratios, the convergent nozzles of various exit shapes (circular, square, rectangular, and elliptical) all appeared to have essentially the same sound field. All these nozzles exhibited sound spectra having discrete-frequency-type noises due to shock waves.

3. At high jet pressure ratios, considerable noise reduction was achieved by use of a convergent-divergent nozzle. The particular nozzle investigated produced one-third to one-half as much sound power as a convergent nozzle at a pressure ratio near 2.9. This reduction in sound power resulted from the elimination of discrete frequencies due to shock waves.

4. The series of plug nozzles (designed for high jet pressure ratios) investigated did not show the reduction in sound power or discrete

frequencies obtained with the convergent-divergent nozzle. These nozzles showed characteristics similar to convergent nozzles over a range of jet pressure ratios from 1.45 to 4.2.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, October 19, 1955

3838

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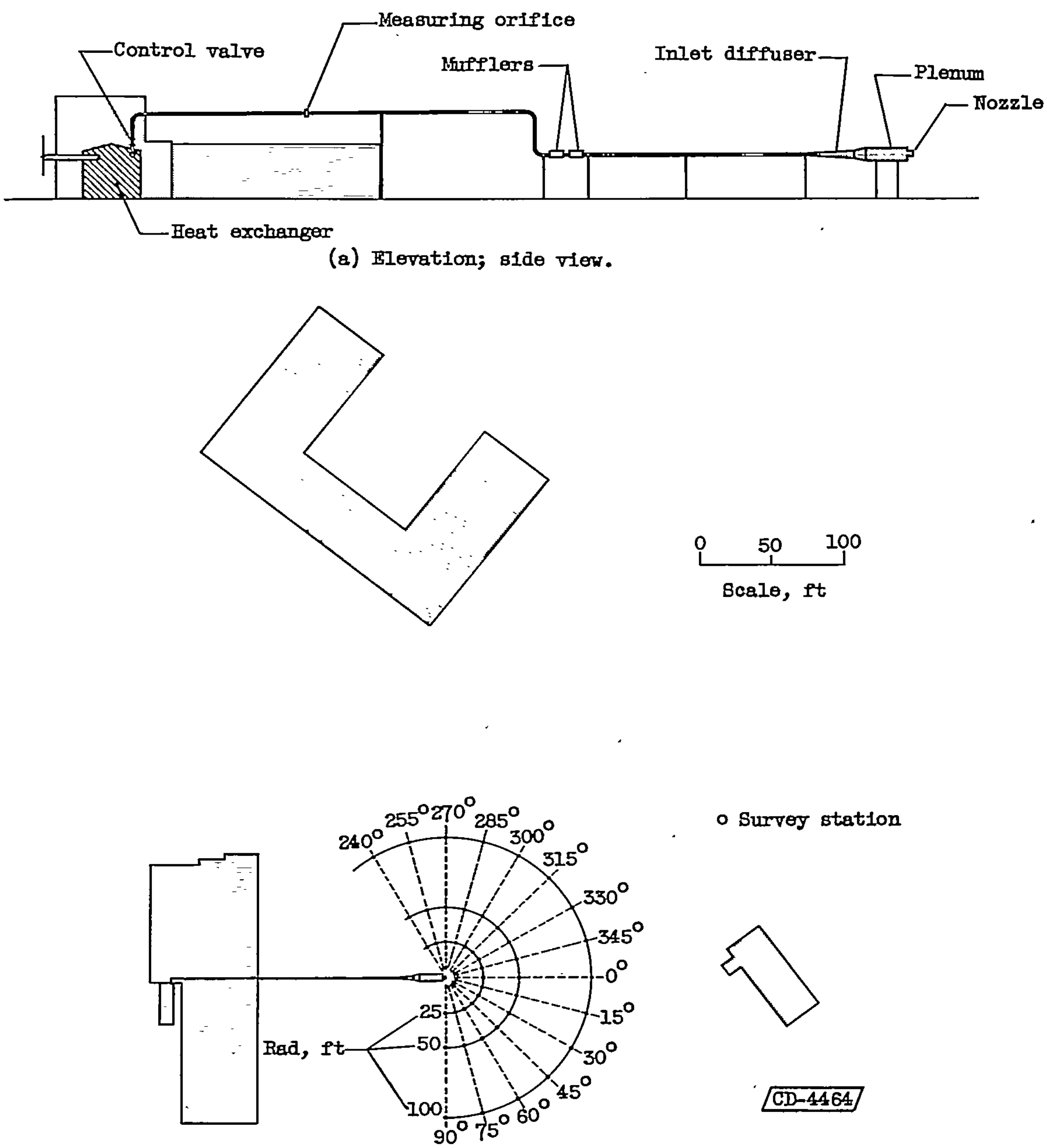

Figure 1. - Schematic diagram of air system and adjacent buildings.

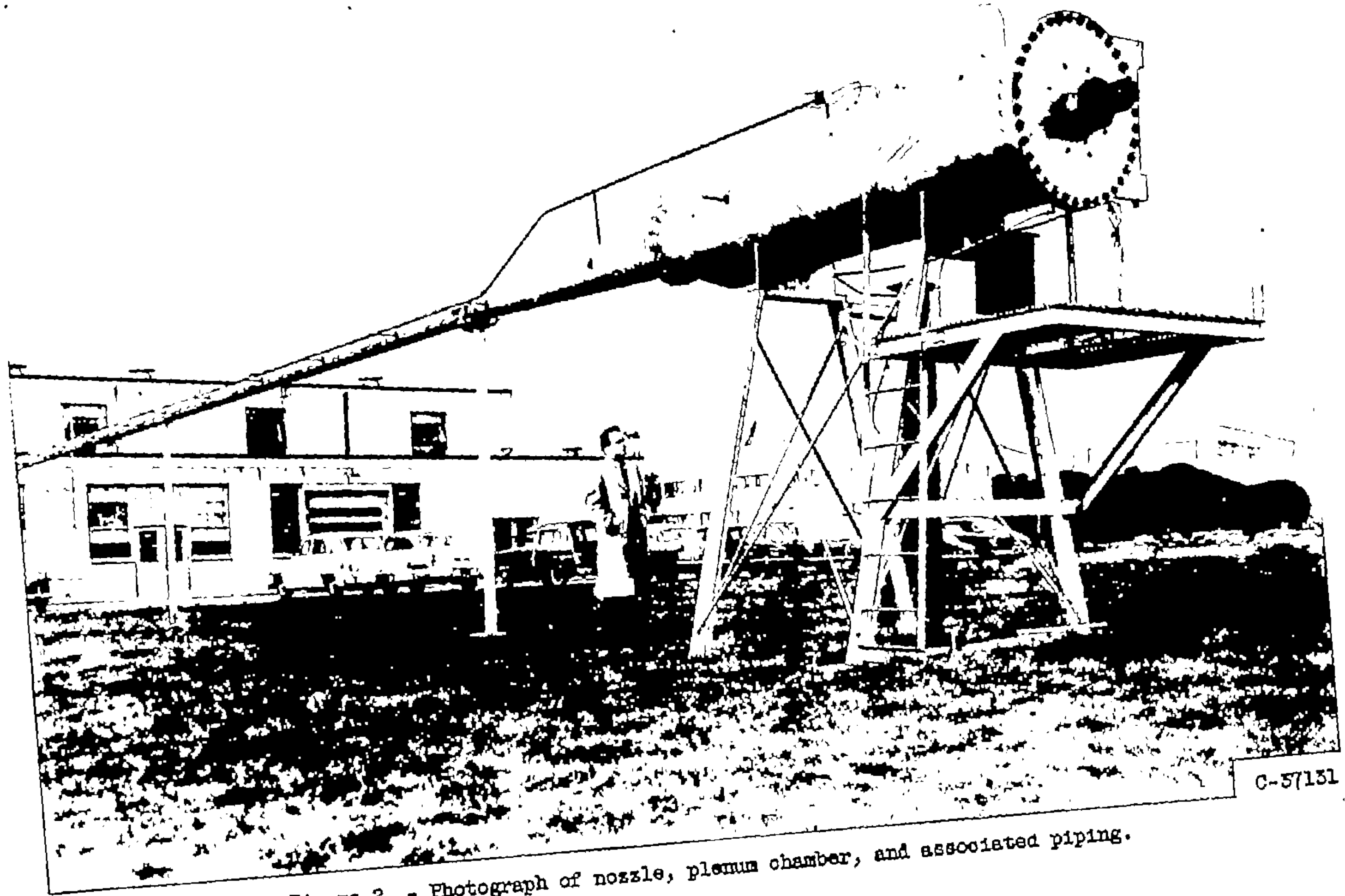

Figure 2. - Photograph of nozzle, plenum chamber, and associated piping.

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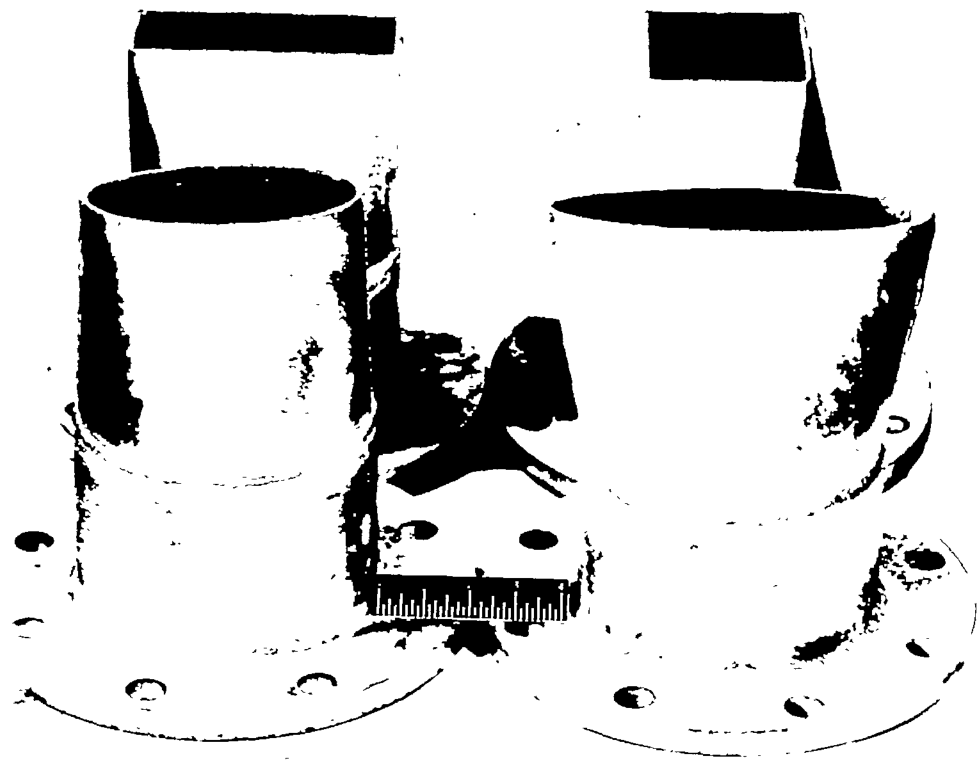

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Figure 3. - Square, rectangular, and elliptical convergent nozzles.

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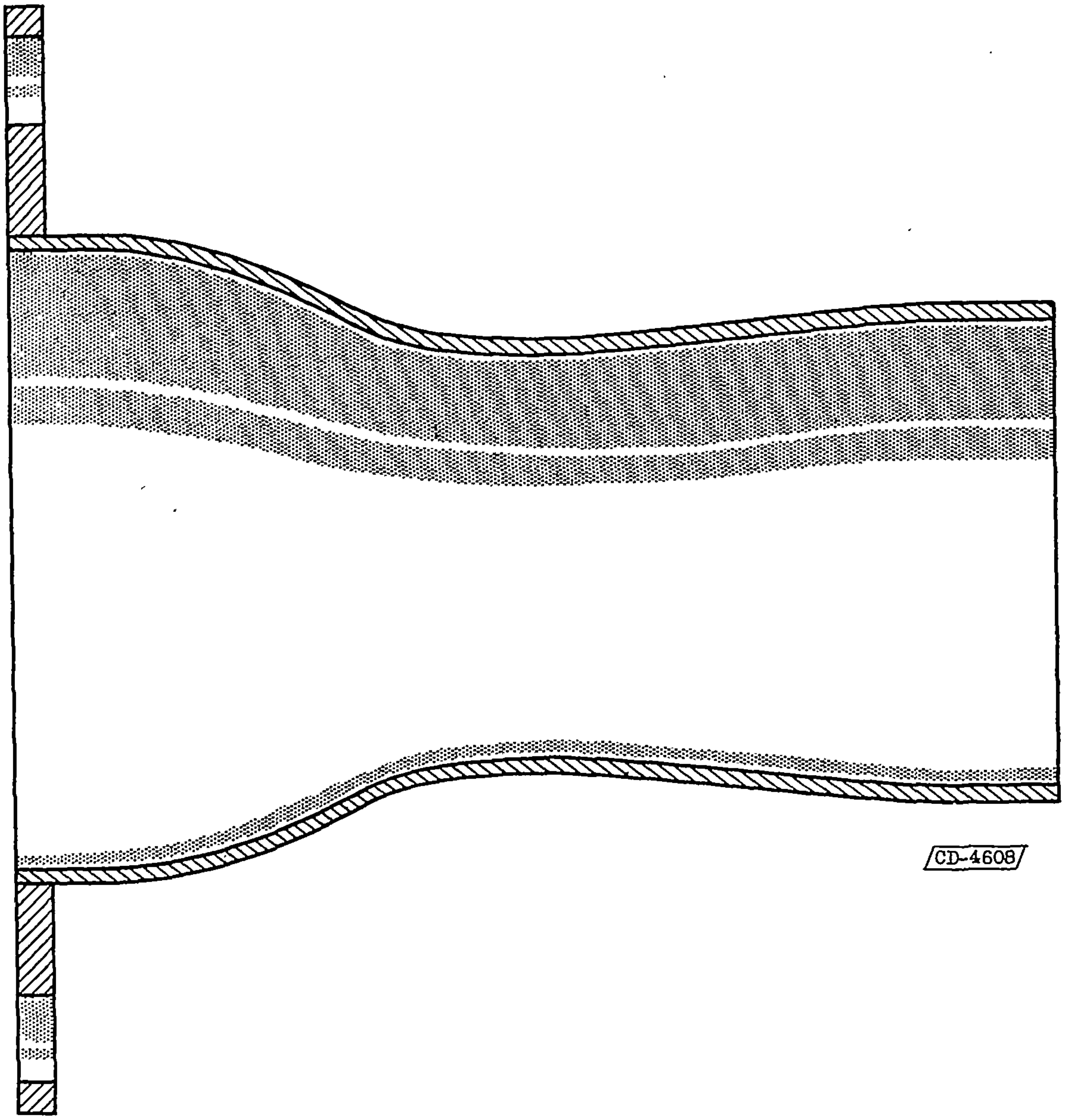

(a) Convergent-divergent nozzle; design pressure ratio, 3.0; 4-inch-diameter throat.

Figure 4. - Nozzles designed for high pressure ratios.

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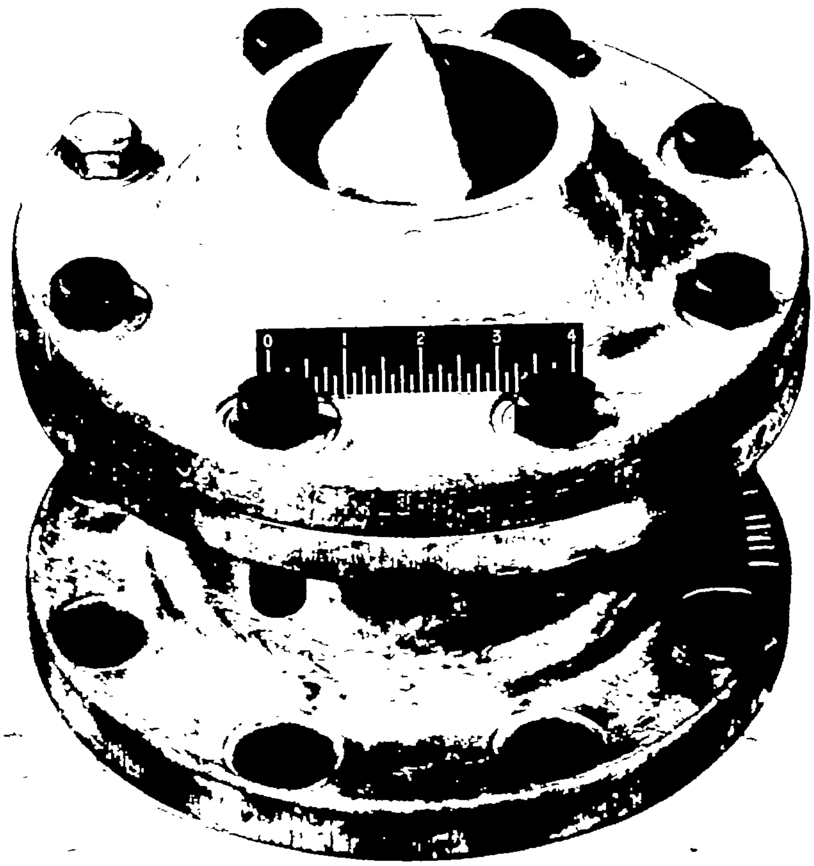

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(b) Conical plug; design pressure ratio, 4.0.

Figure 4. - Continued. Nozzles designed for high pressure ratios.

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(c) Conical plug; design pressure ratio, 9.5.

Figure 4. - Continued. Nozzles designed for high pressure ratios.

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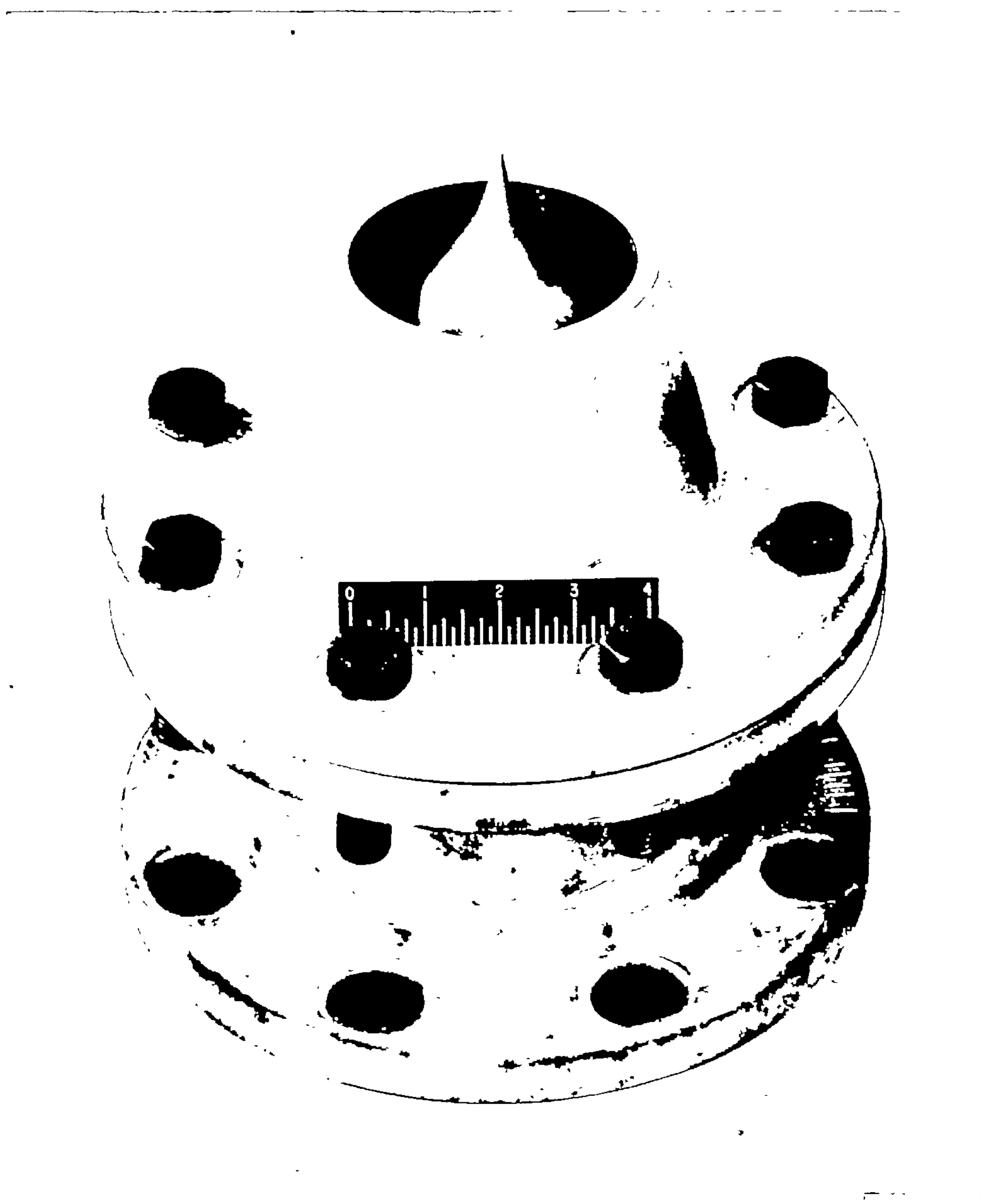

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(d) Isentropic plug; design pressure ratio, 4.0.

Figure 4. - Continued. Nozzles designed for high pressure ratios.

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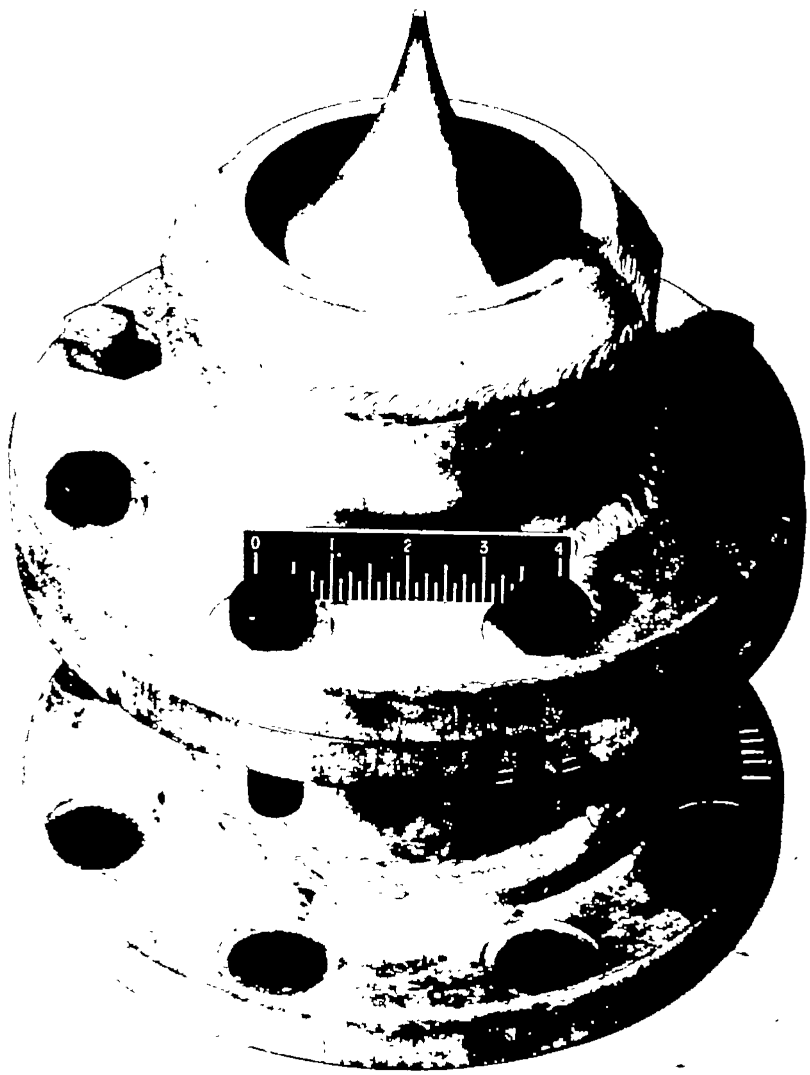

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(e) Isentropic plug; design pressure ratio, 9.5.

Figure 4. - Concluded. Nozzles designed for high pressure ratios.

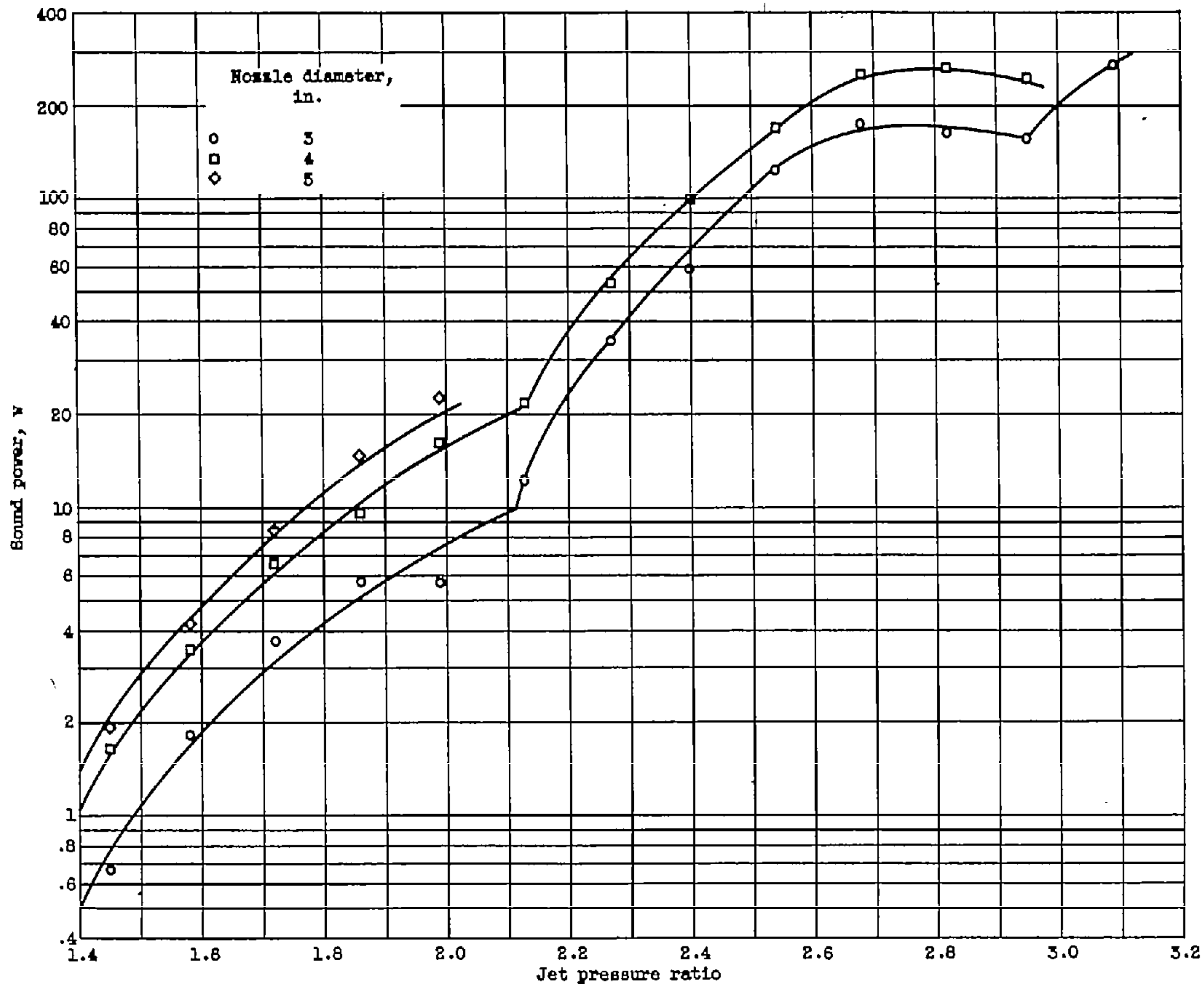


Figure 5. - Sound power as function of jet pressure ratio for three circular convergent nozzles.

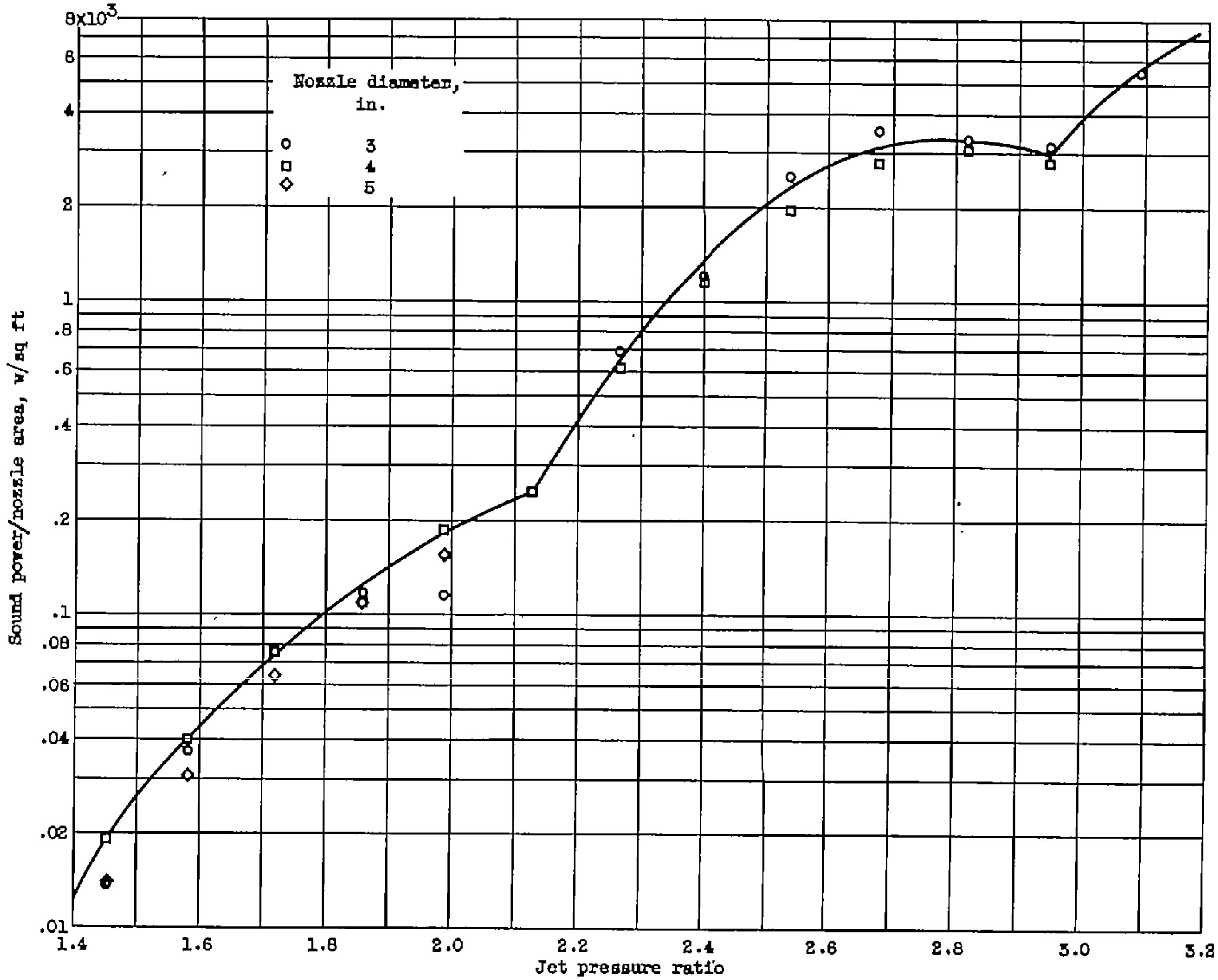


Figure 8. - Sound power per unit nozzle area as function of jet pressure ratio for circular convergent nozzles.

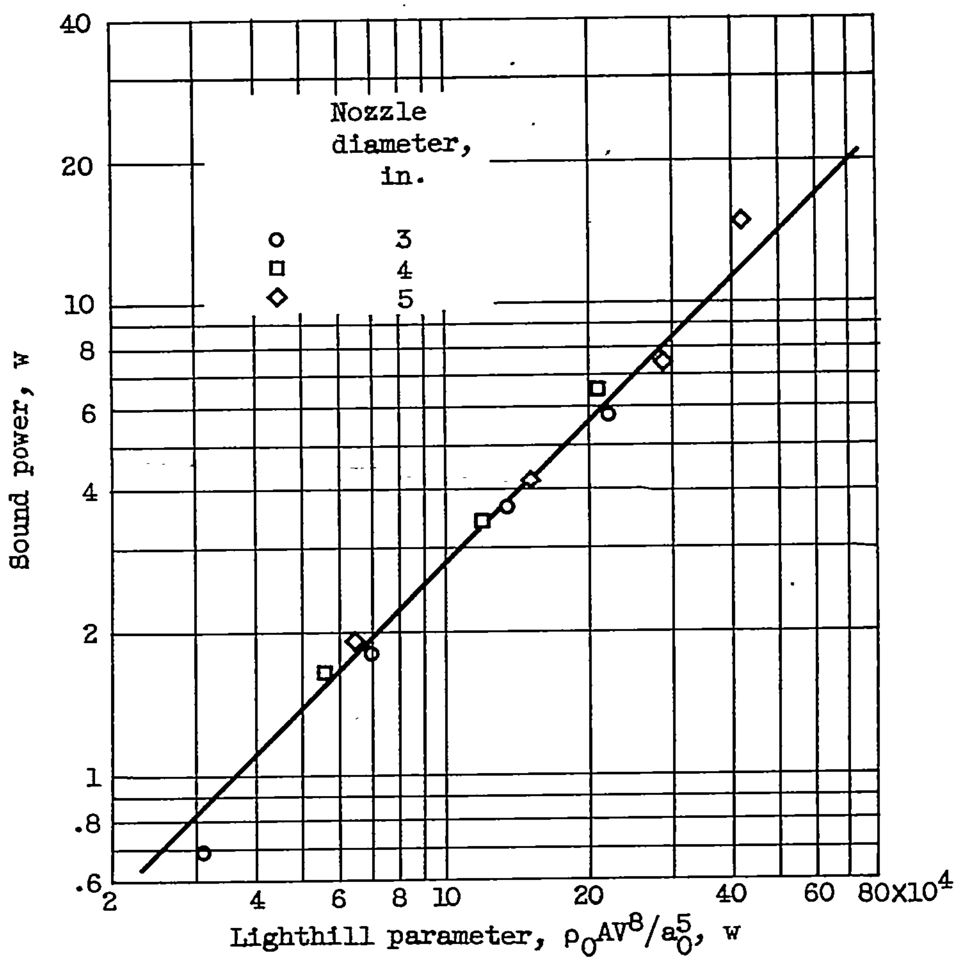


Figure 7. - Sound power as function of Lighthill parameter (ref. 6) for three circular convergent nozzles. Pressure ratio, less than 1.89.

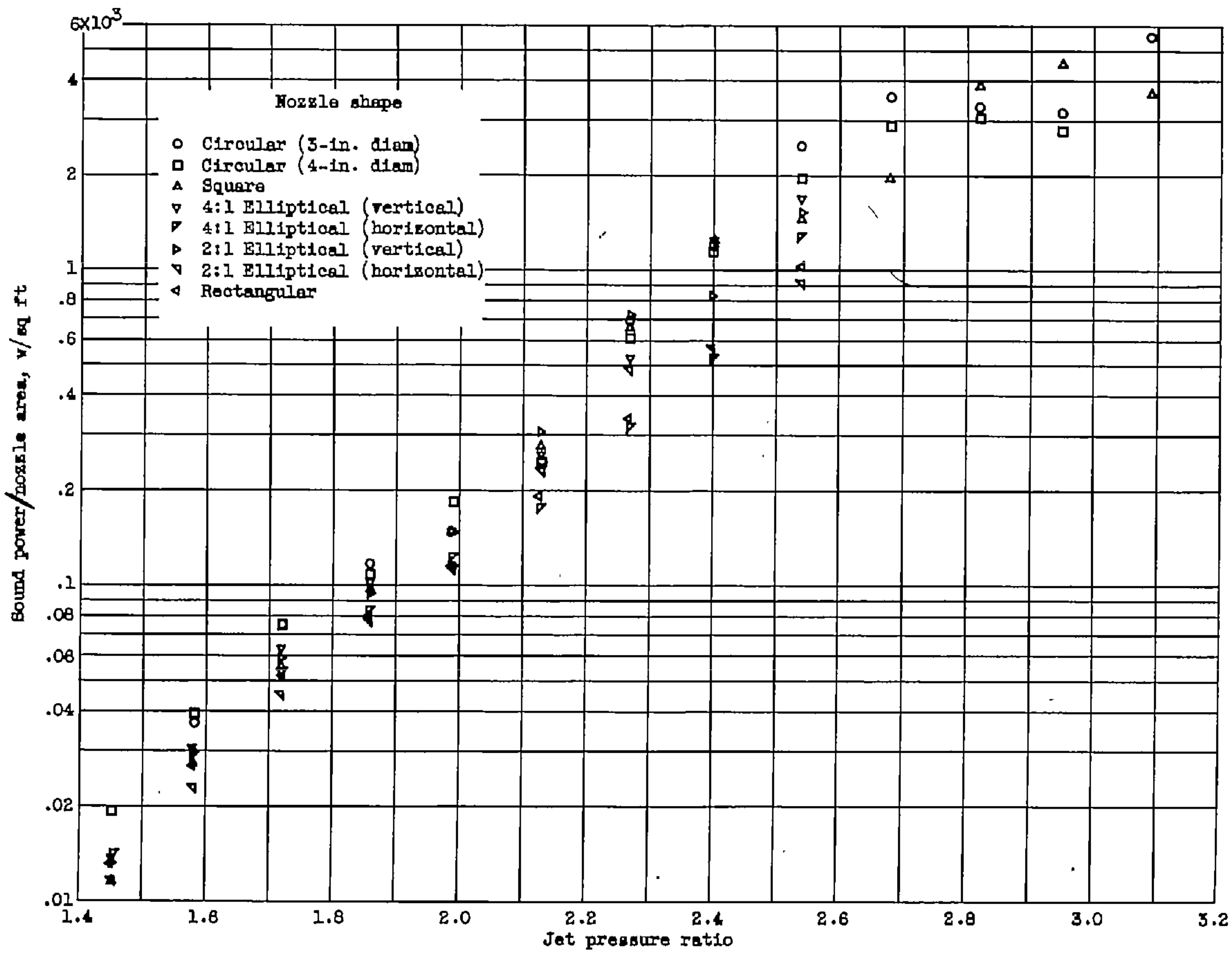


Figure 8. - Effect of nozzle shape on sound-power generation.

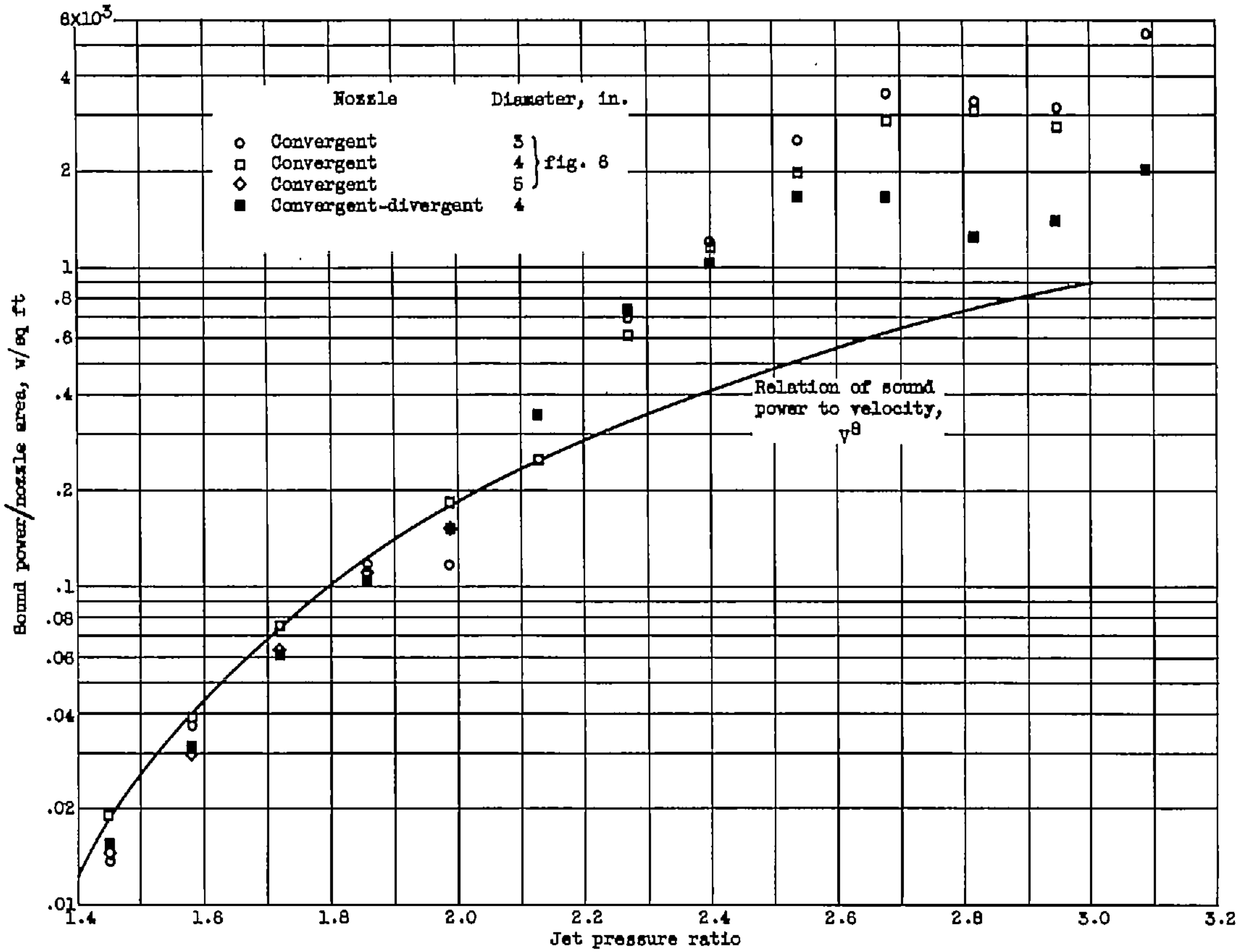


Figure 9. - Comparison of sound power generated by jets discharging from convergent and convergent-divergent nozzles.

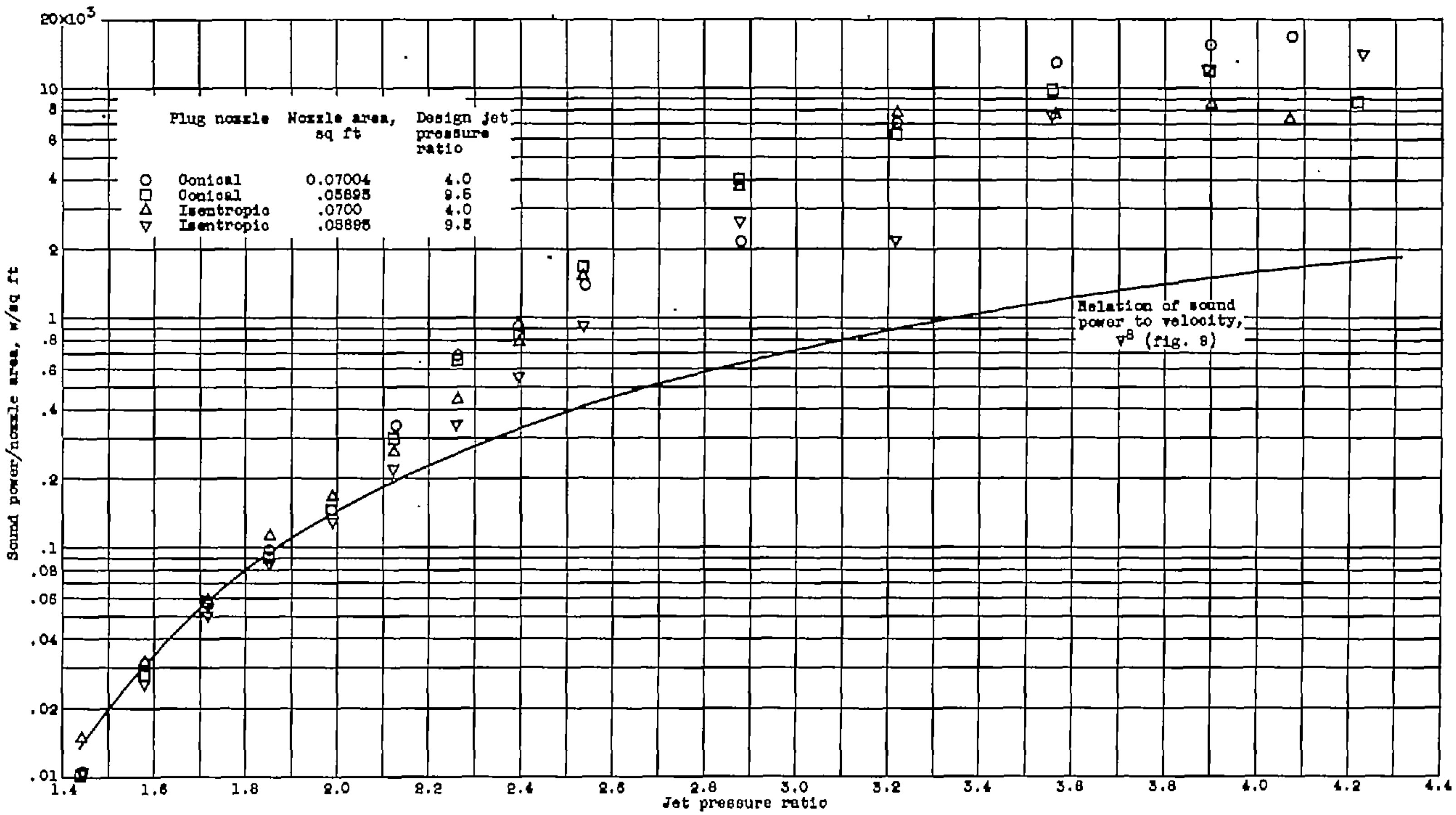


Figure 10. - Comparison of sound power generated by jets discharging from plug nozzles.

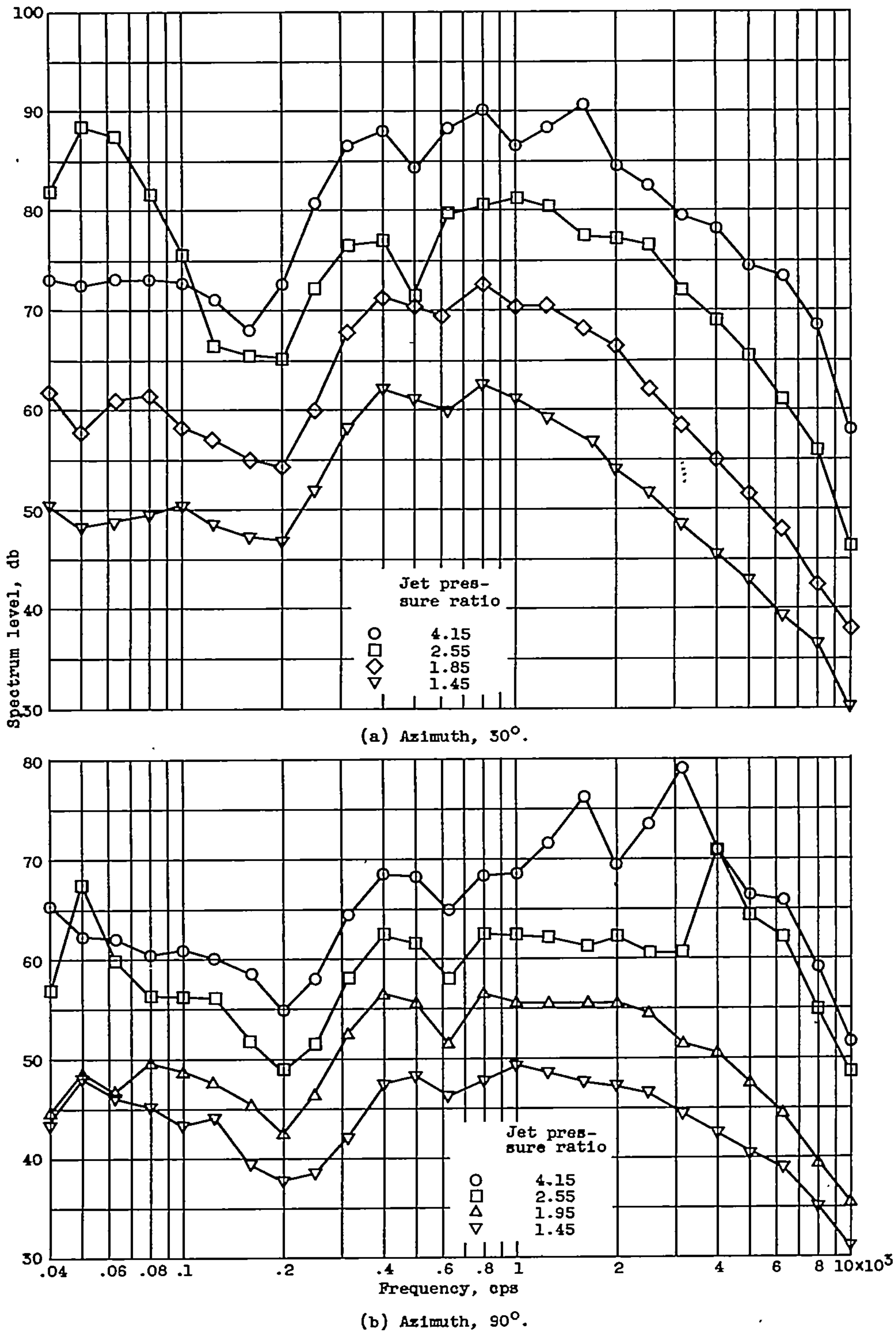
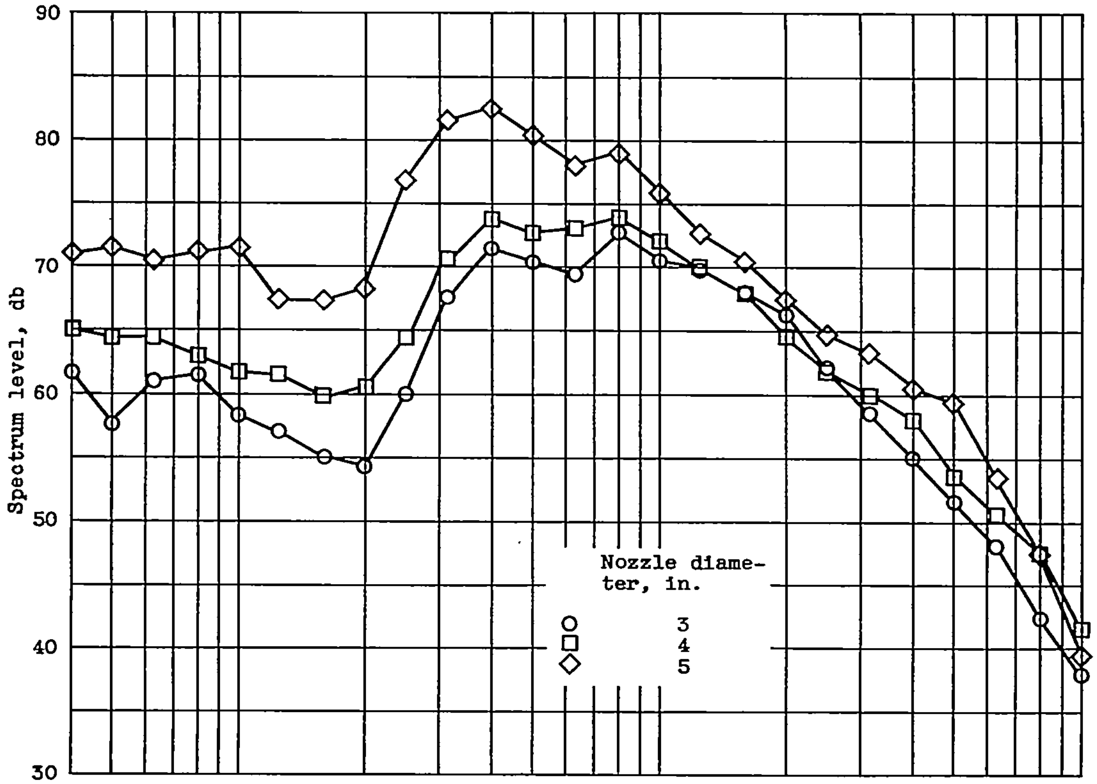
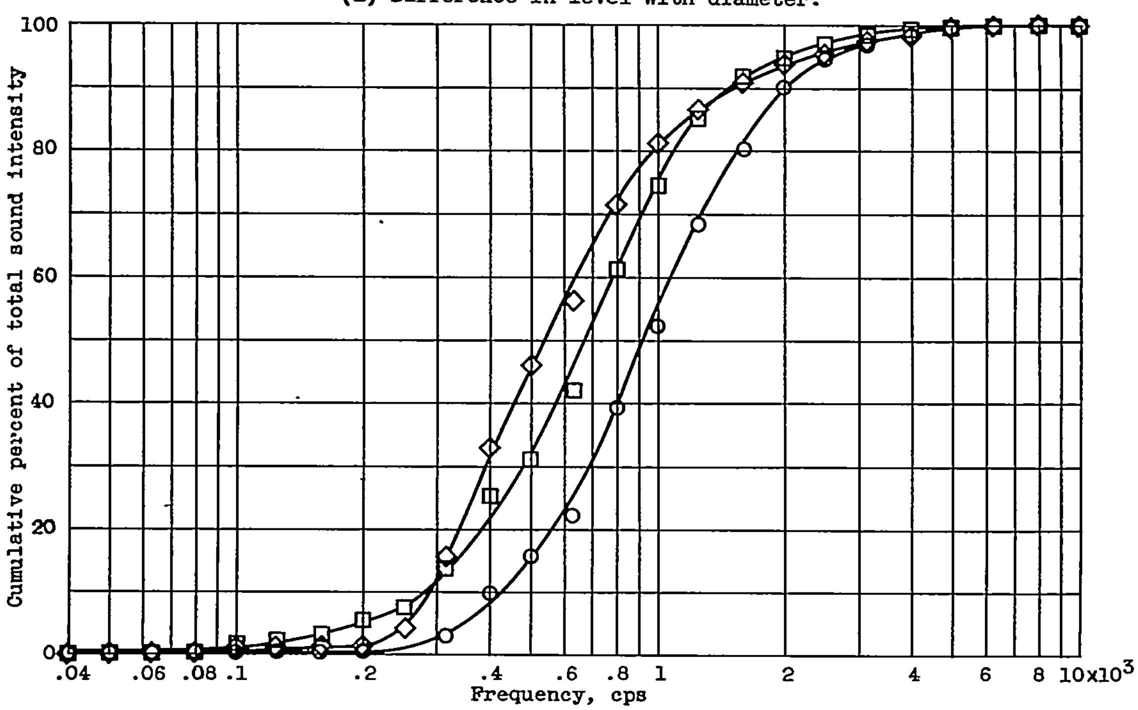


Figure 11. - Sound spectra of jet discharging from 3-inch-diameter convergent nozzle. Distance from jet exit, 50 feet.



(a) Difference in level with diameter.



(b) Frequency shift with nozzle diameter.

Figure 12. - Effect of convergent nozzle diameter on sound spectra. Jet pressure ratio, 1.85; azimuth, 30°.

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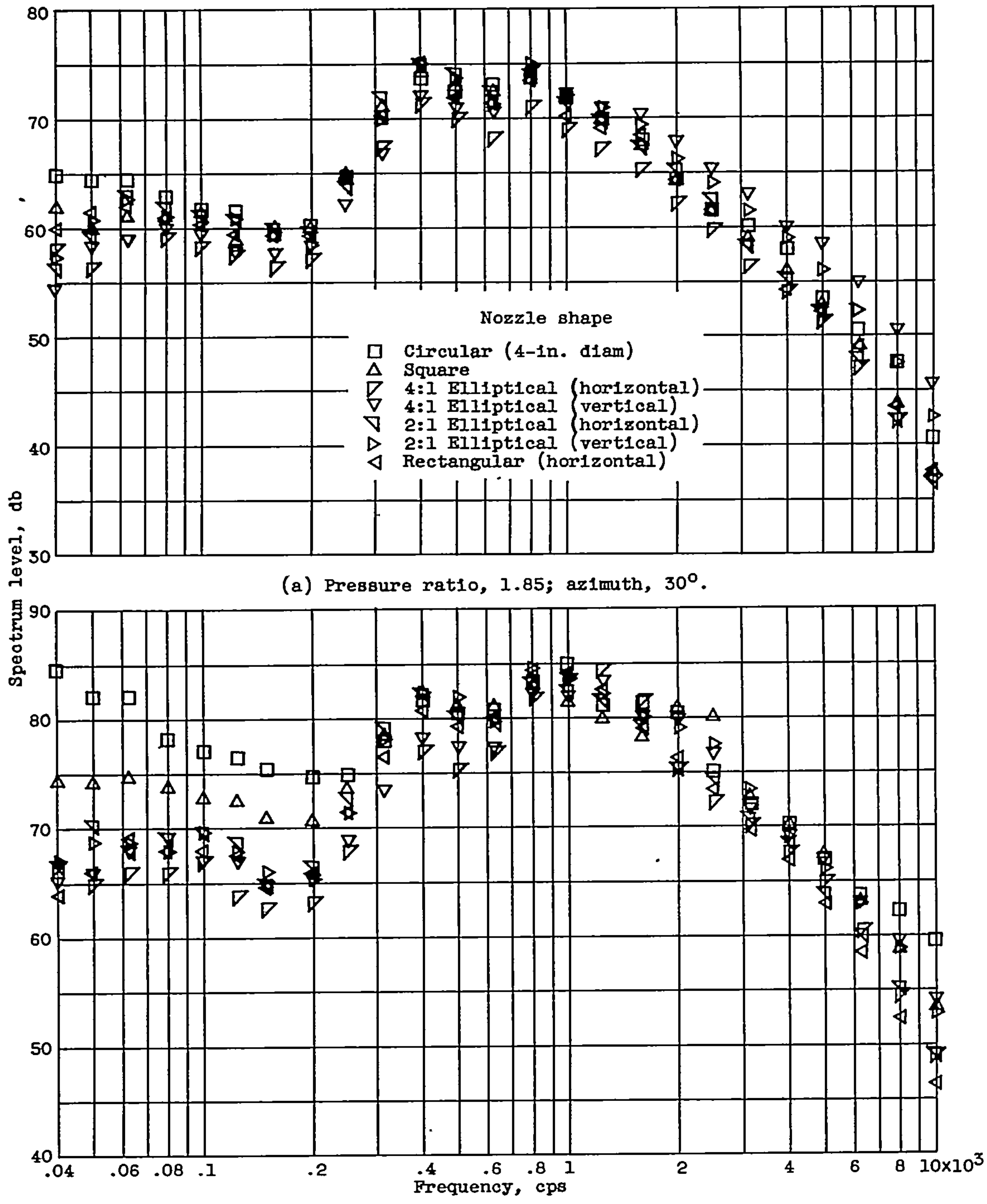

(a) Pressure ratio, 1.85; azimuth, 30°.

(b) Pressure ratio, 2.55; azimuth, 30°.

Figure 13. - Sound spectra of various convergent-nozzle shapes. Distance from jet exit, 50 feet.

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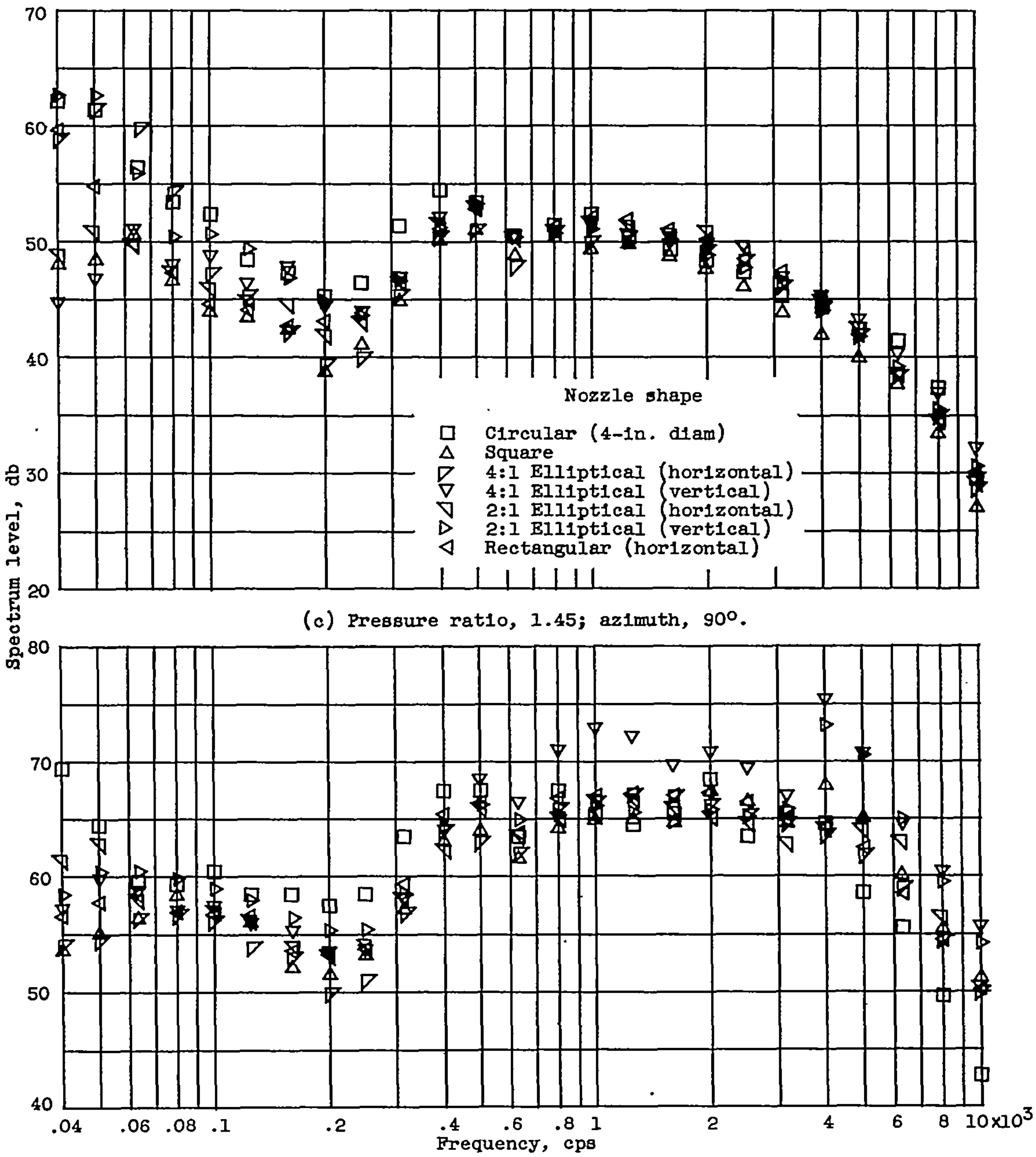

(d) Pressure ratio, 2.55; azimuth, 90°.

Figure 13. - Concluded. Sound spectra of various convergent-nozzle shapes. Distance from jet exit, 50 feet.

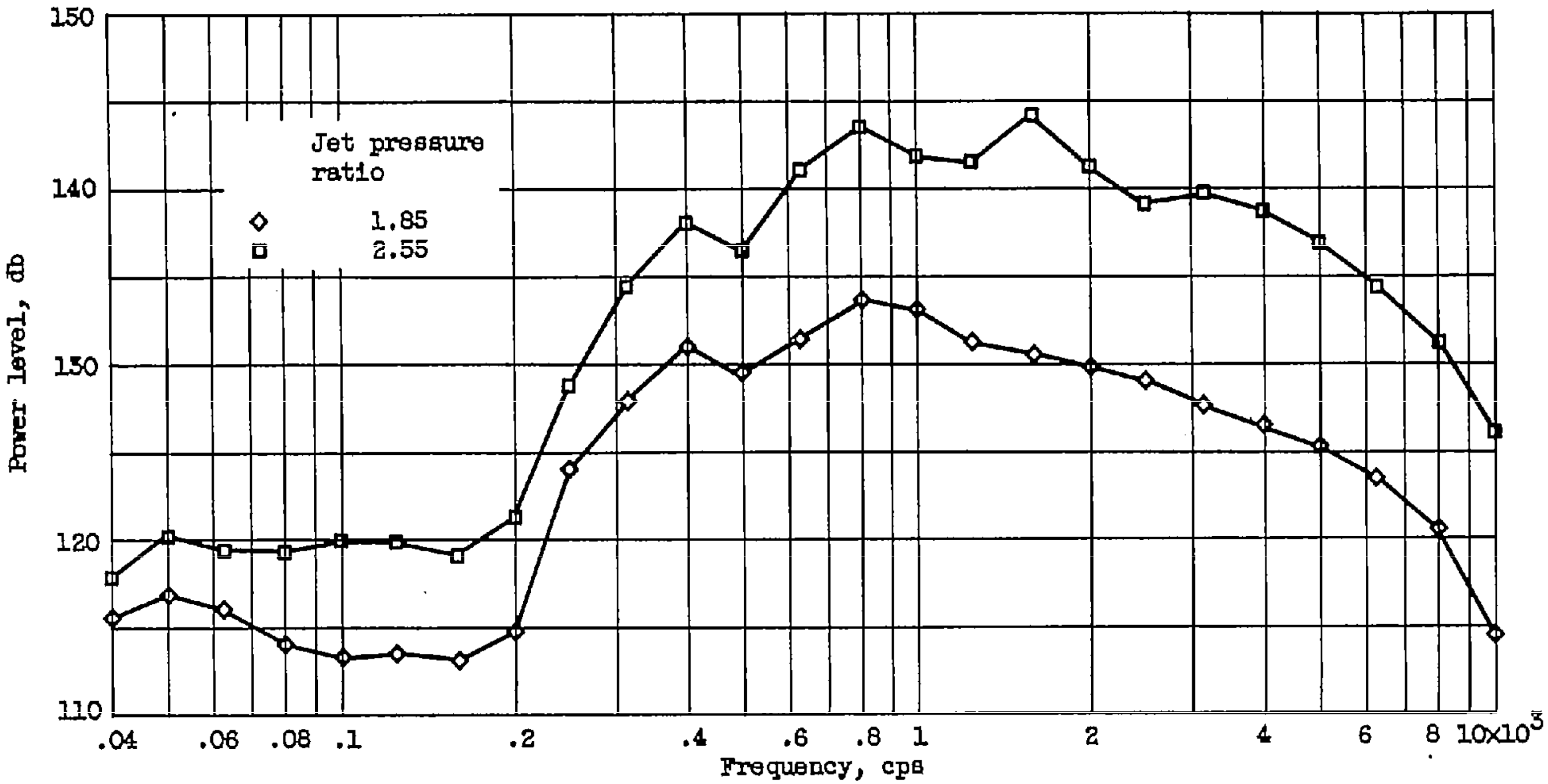

Figure 14. - Sound-power spectra of jet discharging from 4-inch-diameter circular convergent nozzle at several pressure ratios.

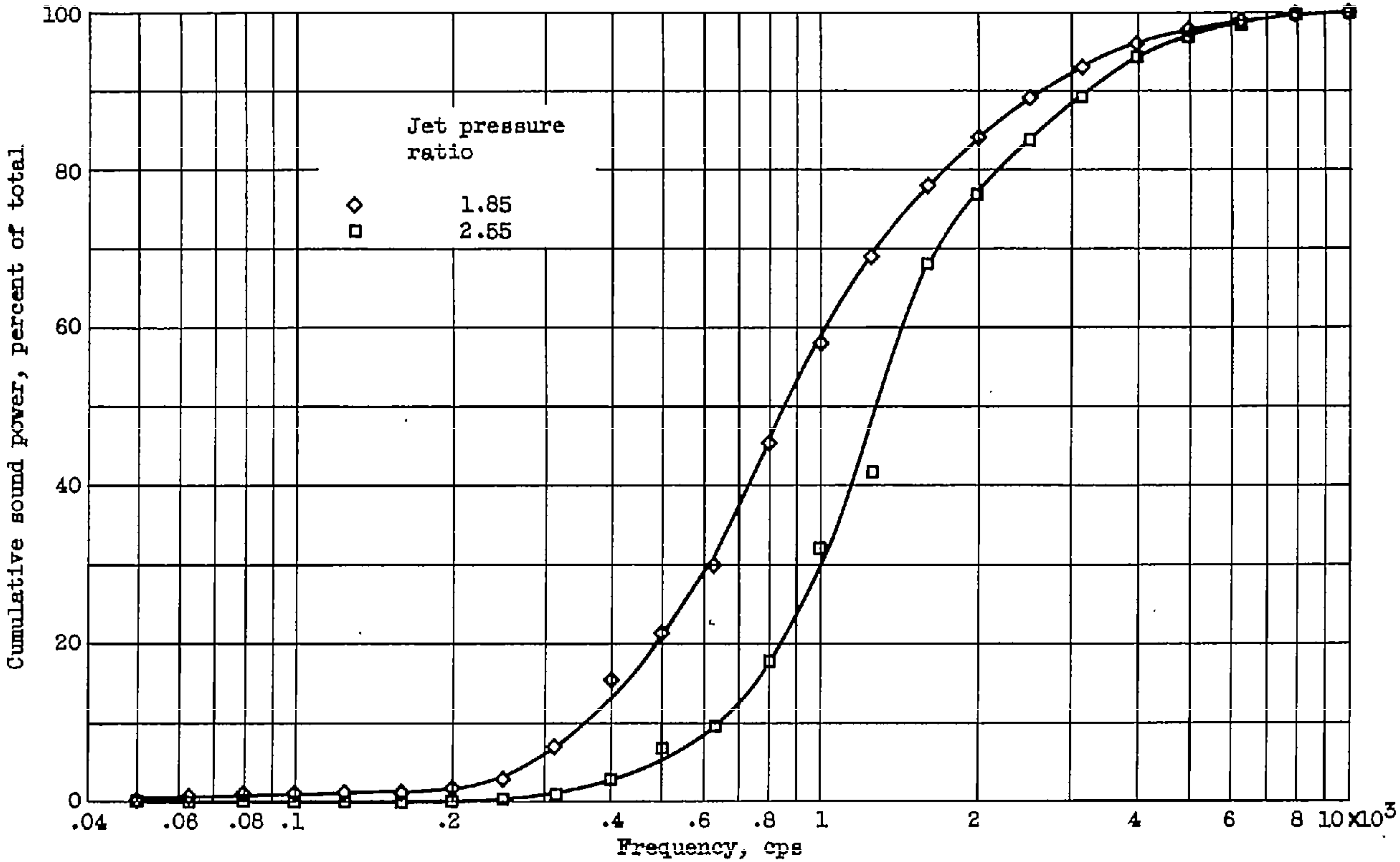

Figure 15. - Cumulative sound power of jet discharging from 4-inch-diameter circular convergent nozzle at several pressure ratios.

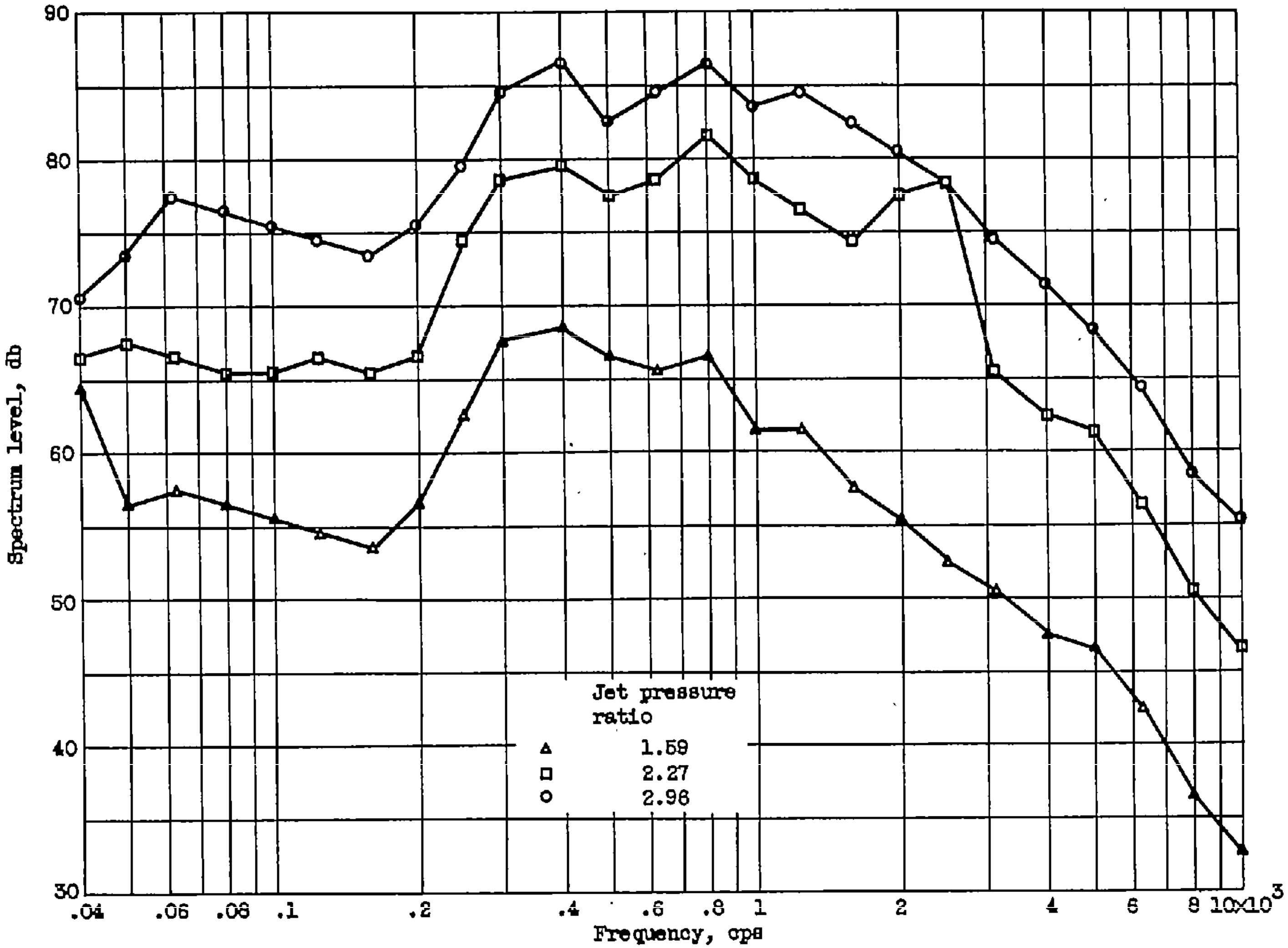

Figure 16. - Sound spectra of jet discharging from convergent-divergent nozzle at several pressure ratios. Distance from jet exit, 50 feet; azimuth, 30°.

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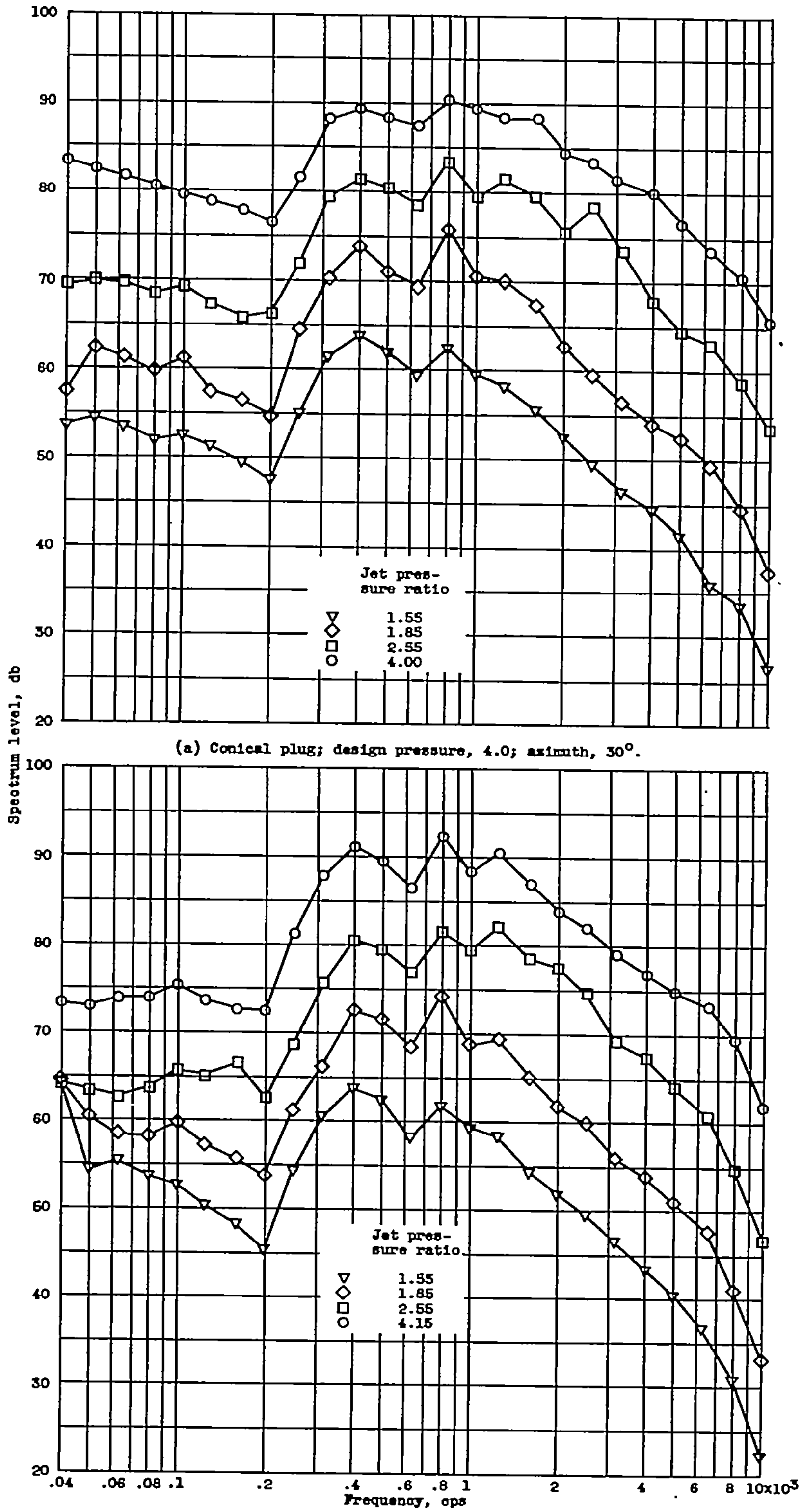
CC-5



(b) Conical plug; design pressure ratio, 9.5; azimuth, 30°.

Figure 17. - Sound spectra of jet discharging from plug nozzle at several pressure ratios. Distance from jet exit, 50 feet.

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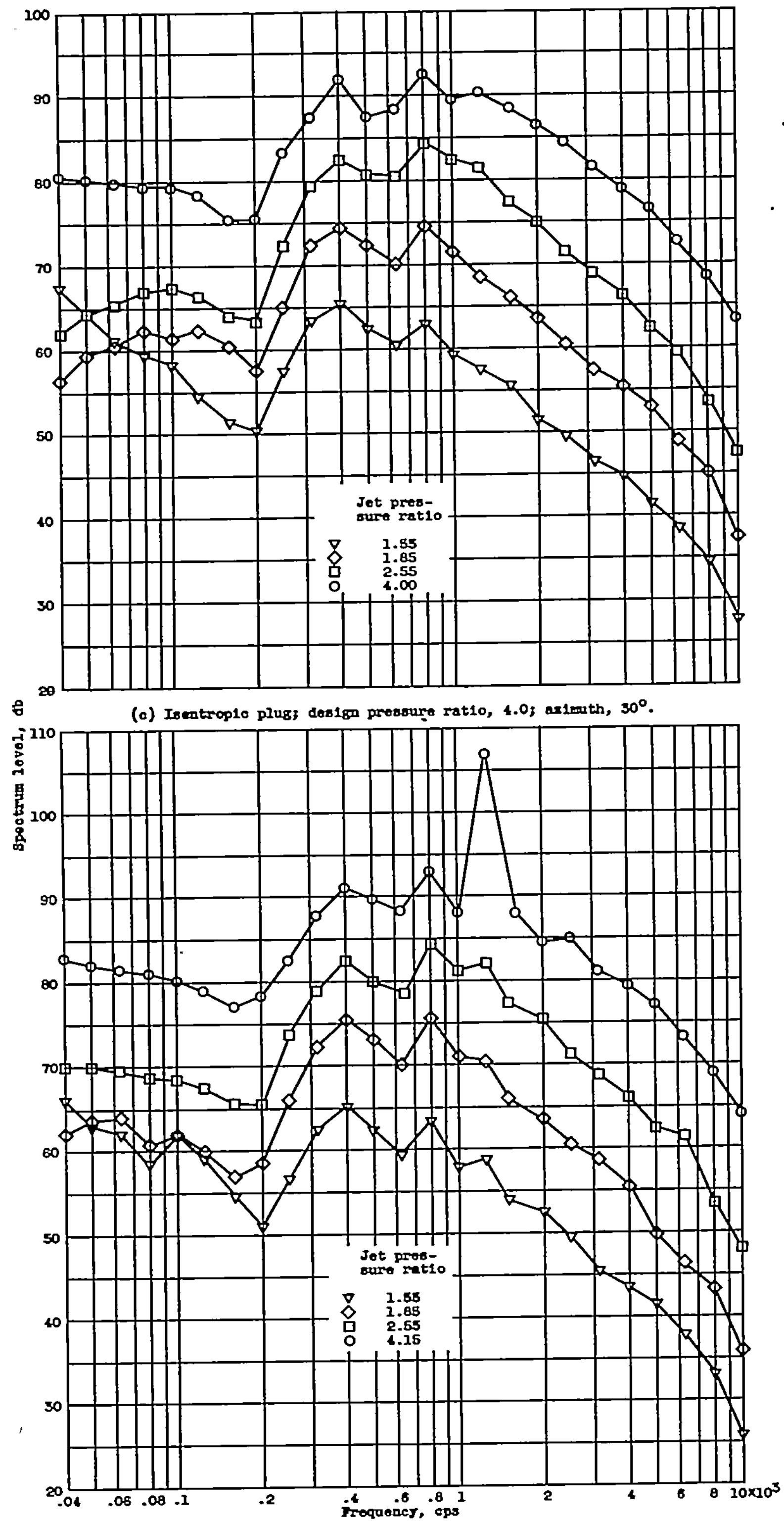

(c) Isentropic plug; design pressure ratio, 4.0; azimuth, 30°.

(d) Isentropic plug; design pressure ratio, 9.5; azimuth, 30°.

Figure 17. - Continued. Sound spectra of jet discharging from plug nozzle at several pressure ratios. Distance from jet exit, 50 feet.

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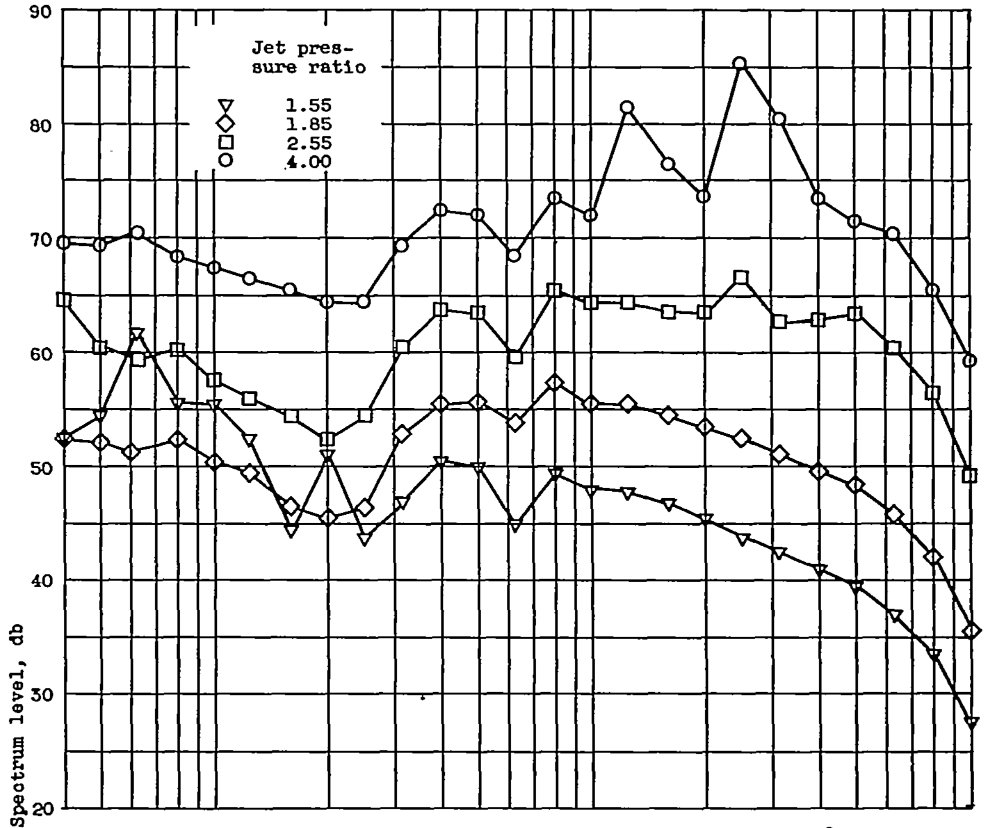
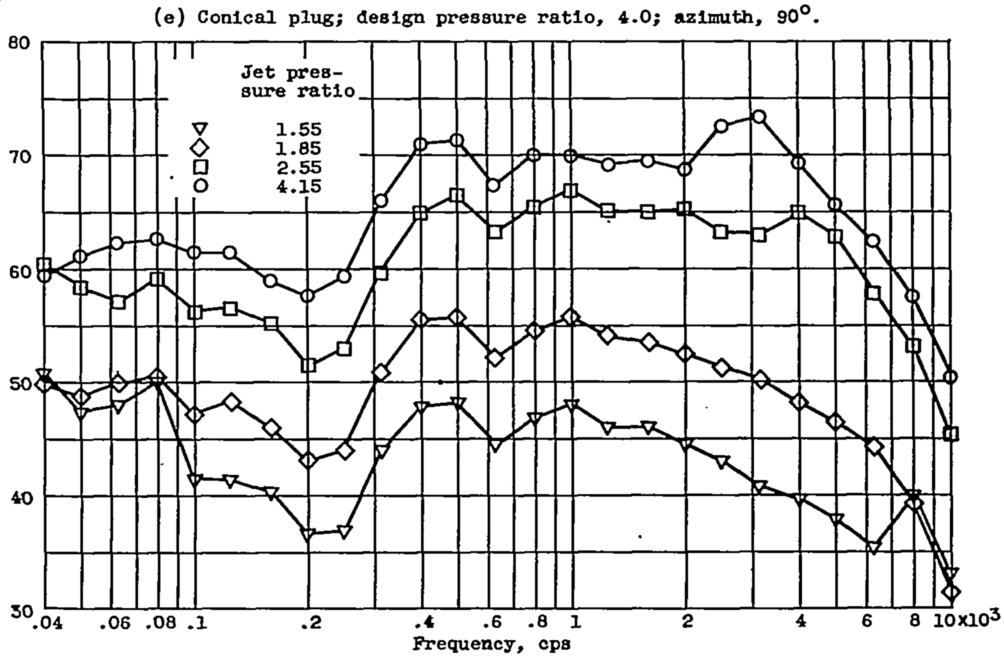
CC-5 back

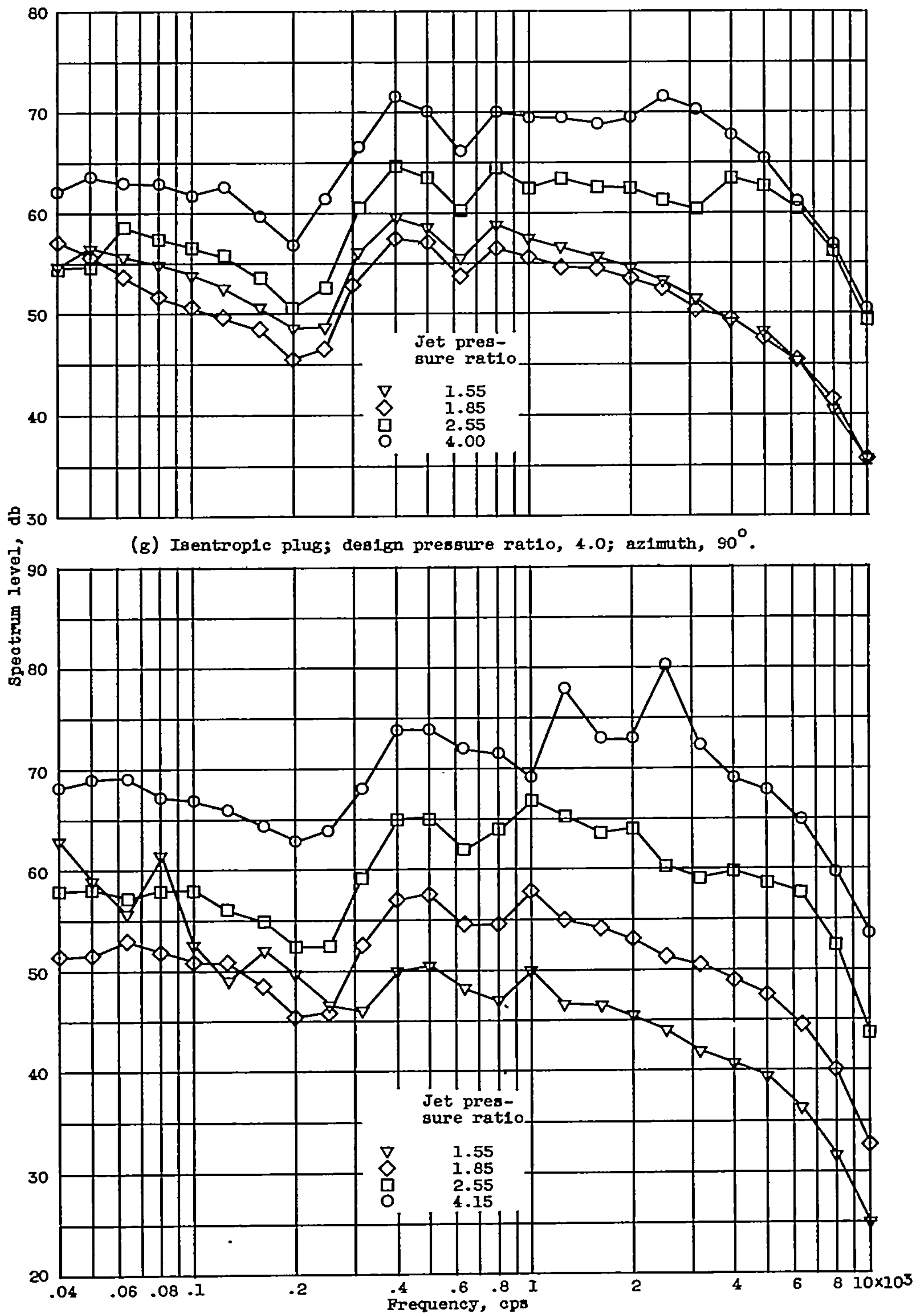


(e) Conical plug; design pressure ratio, 4.0; azimuth, 90°.



(f) Conical plug; design pressure ratio, 9.5; azimuth, 90°.

Figure 17. - Continued. Sound spectra of jet discharging from plug nozzle at several pressure ratios. Distance from jet exit, 50 feet.



(g) Isentropic plug; design pressure ratio, 4.0; azimuth, 90°.

(h) Isentropic plug; design pressure ratio, 9.5; azimuth, 90°.

Figure 17. - Concluded. Sound spectra of jet discharging from plug nozzle at several pressure ratios. Distance from jet exit, 50 feet.

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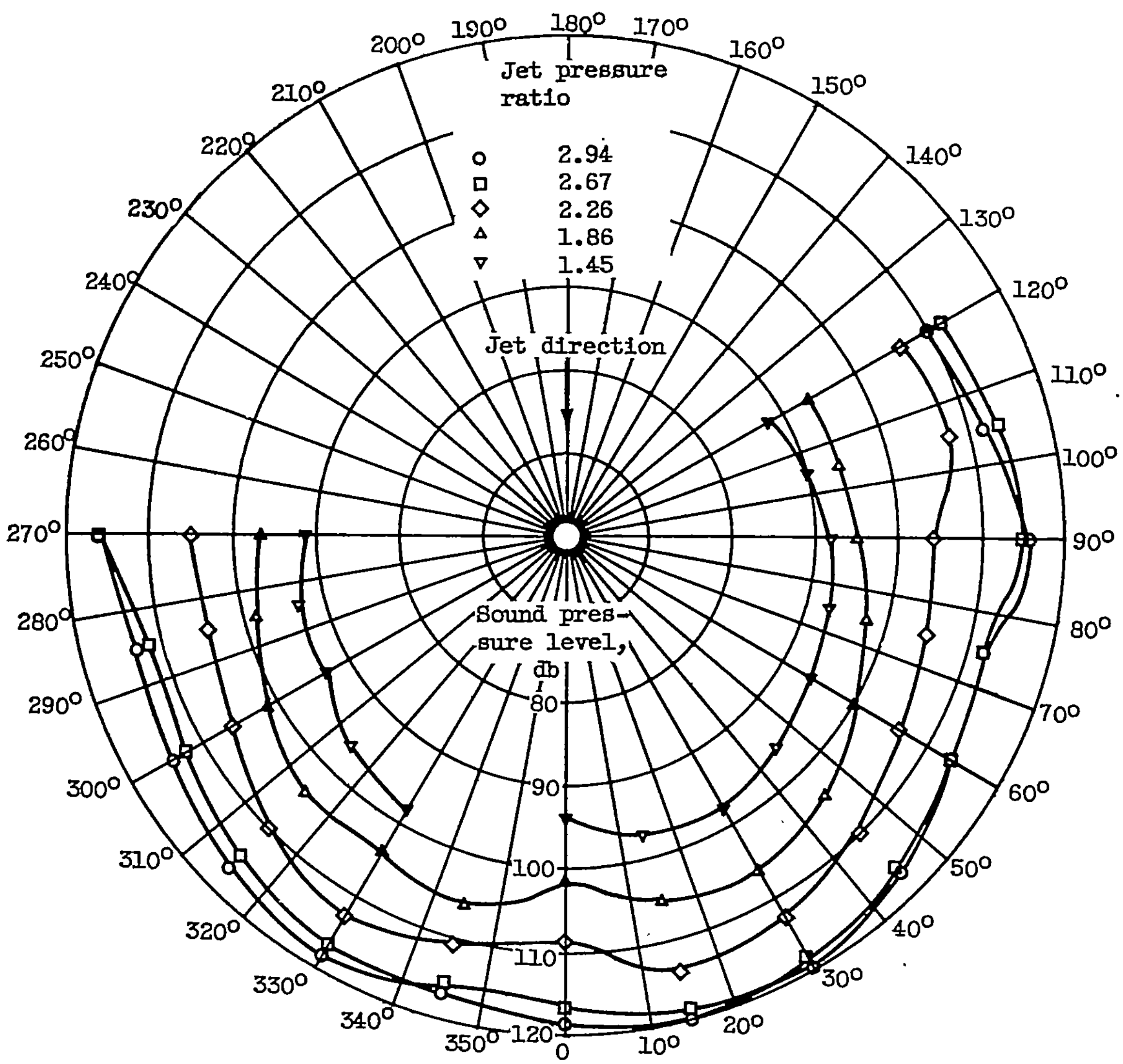
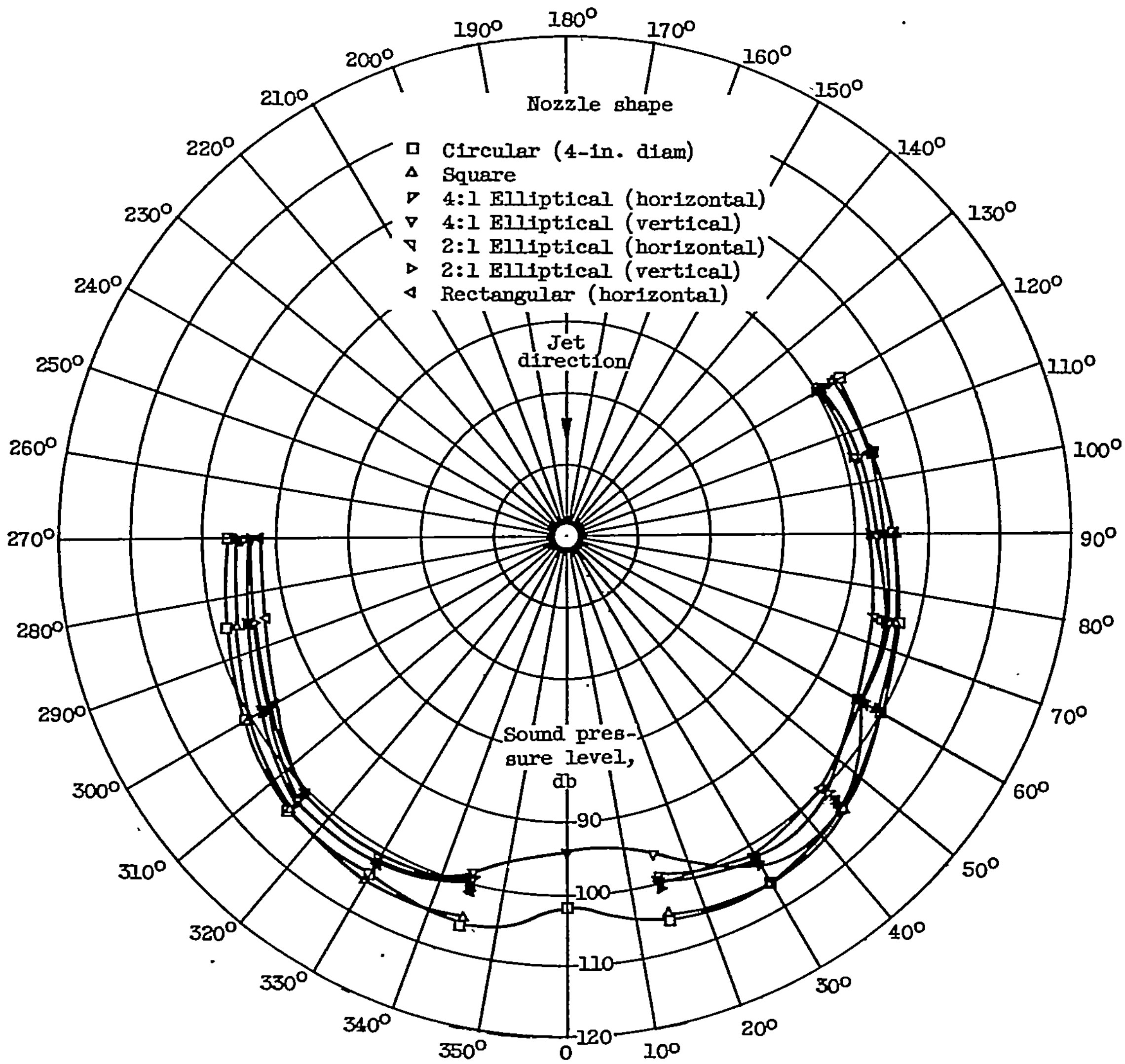


Figure 18. - Polar diagram of sound field for various pressure ratios of 4-inch-diameter circular convergent nozzle. Distance from jet exit, 50 feet.



(a) Jet pressure ratio, 1.85.

Figure 19. - Effect of nozzle shape on sound-field direction. Distance from jet exit, 50 feet.

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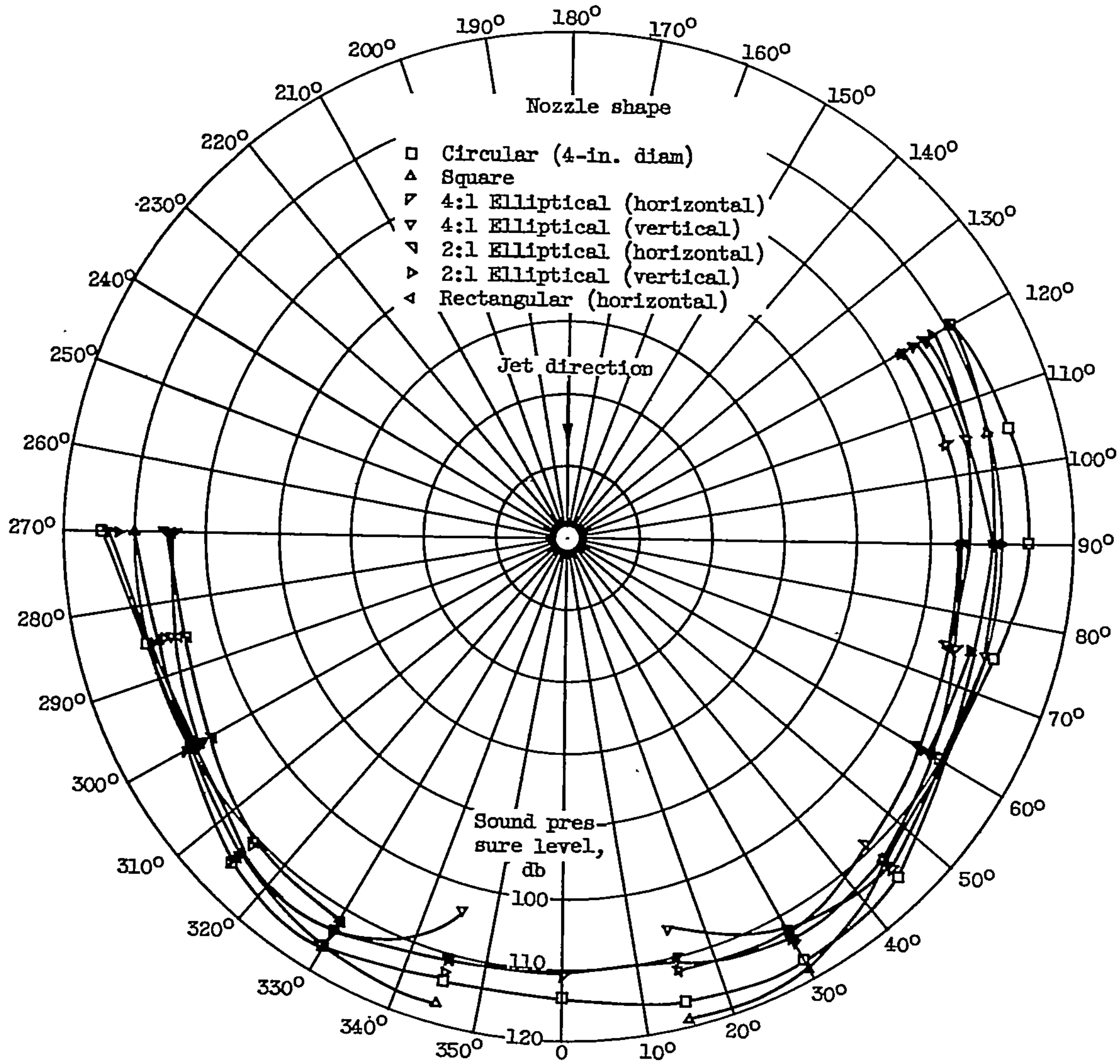

(b) Jet pressure ratio, 2.55.

Figure 19. - Concluded. Effect of nozzle shape on sound-field direction. Distance from jet exit, 50 feet.

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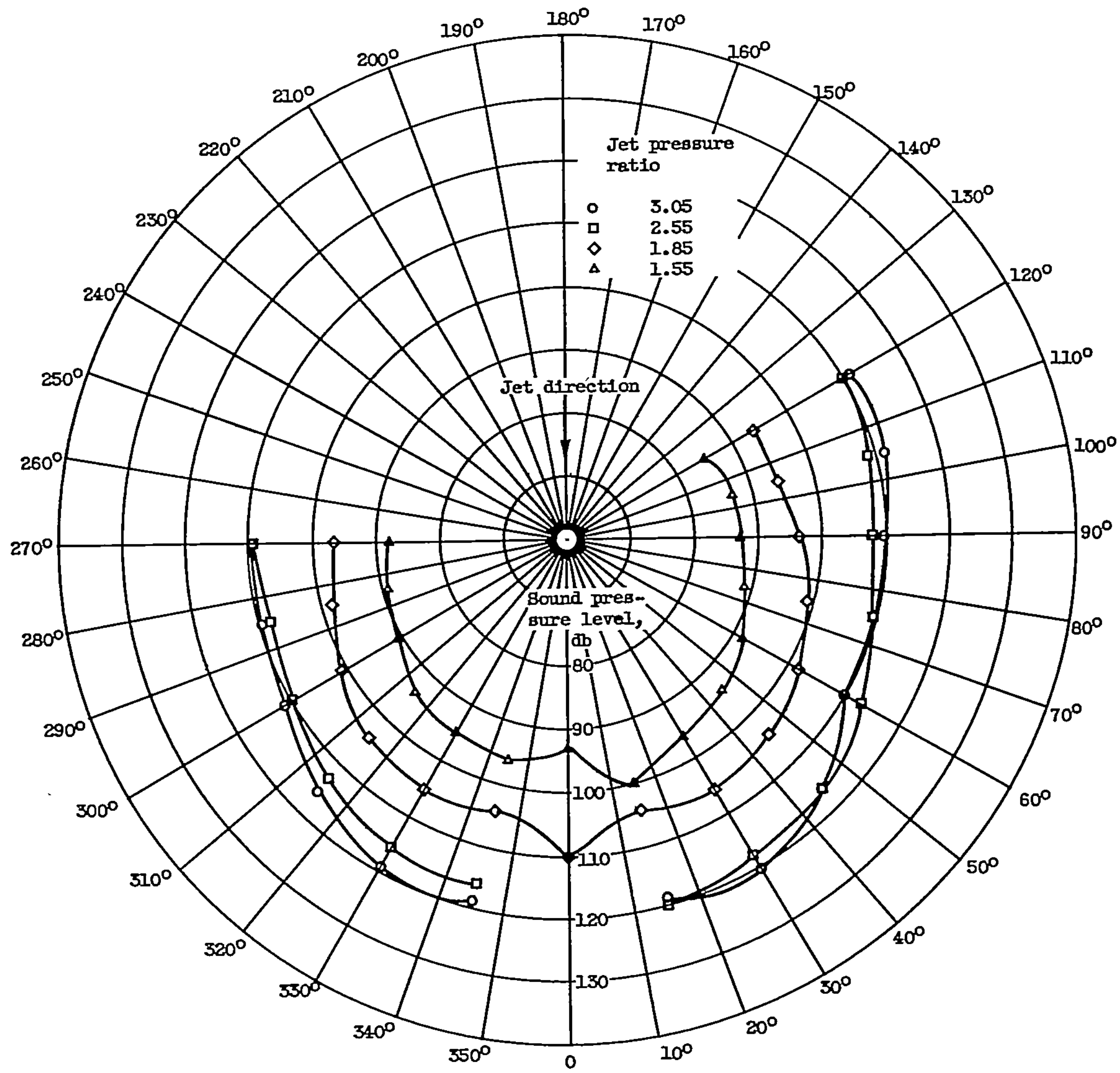

Figure 20. - Sound polar diagram of 4-inch-diameter convergent-divergent nozzle for range of pressure ratios. Distance from jet exit, 50 feet.

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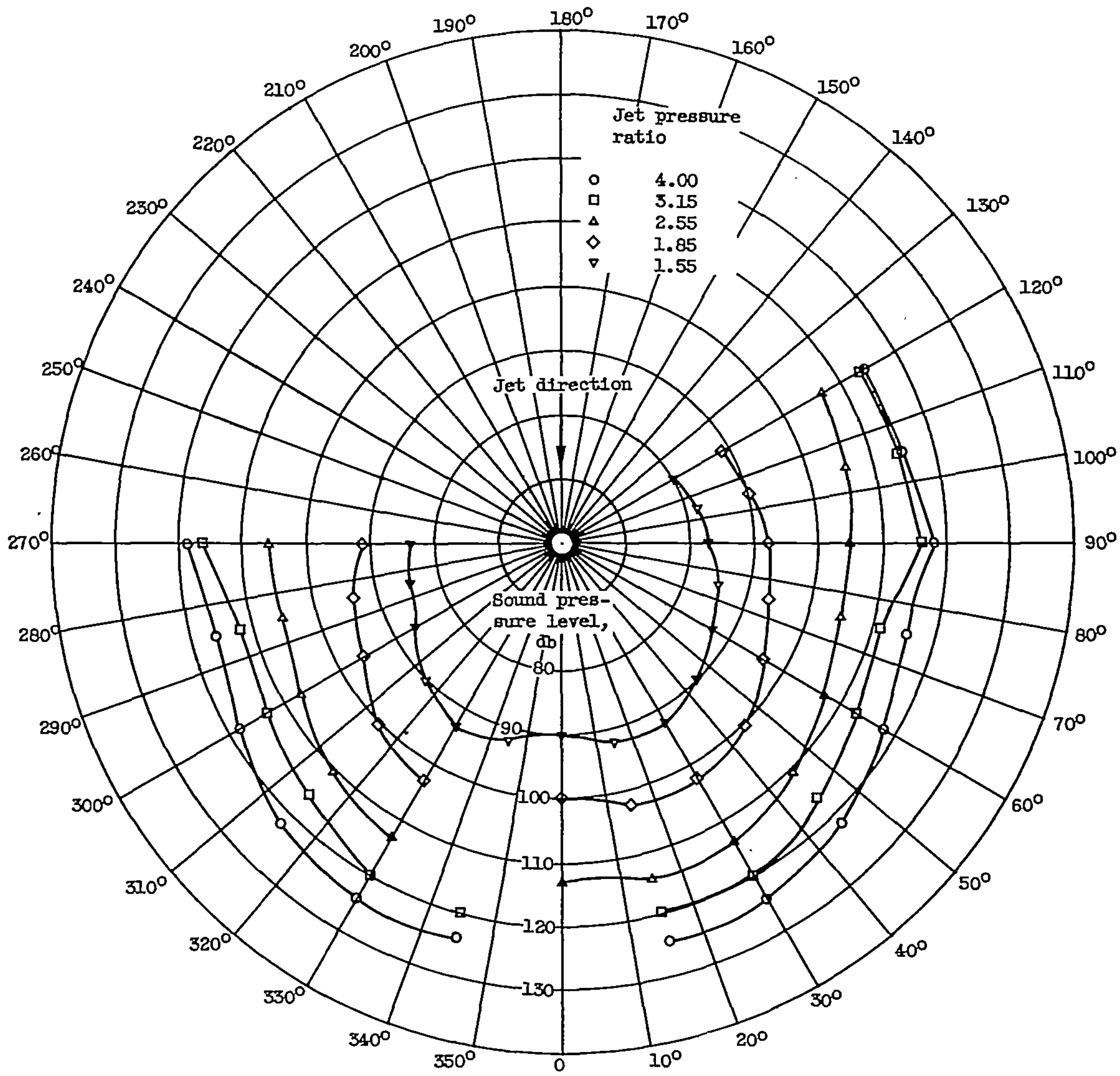
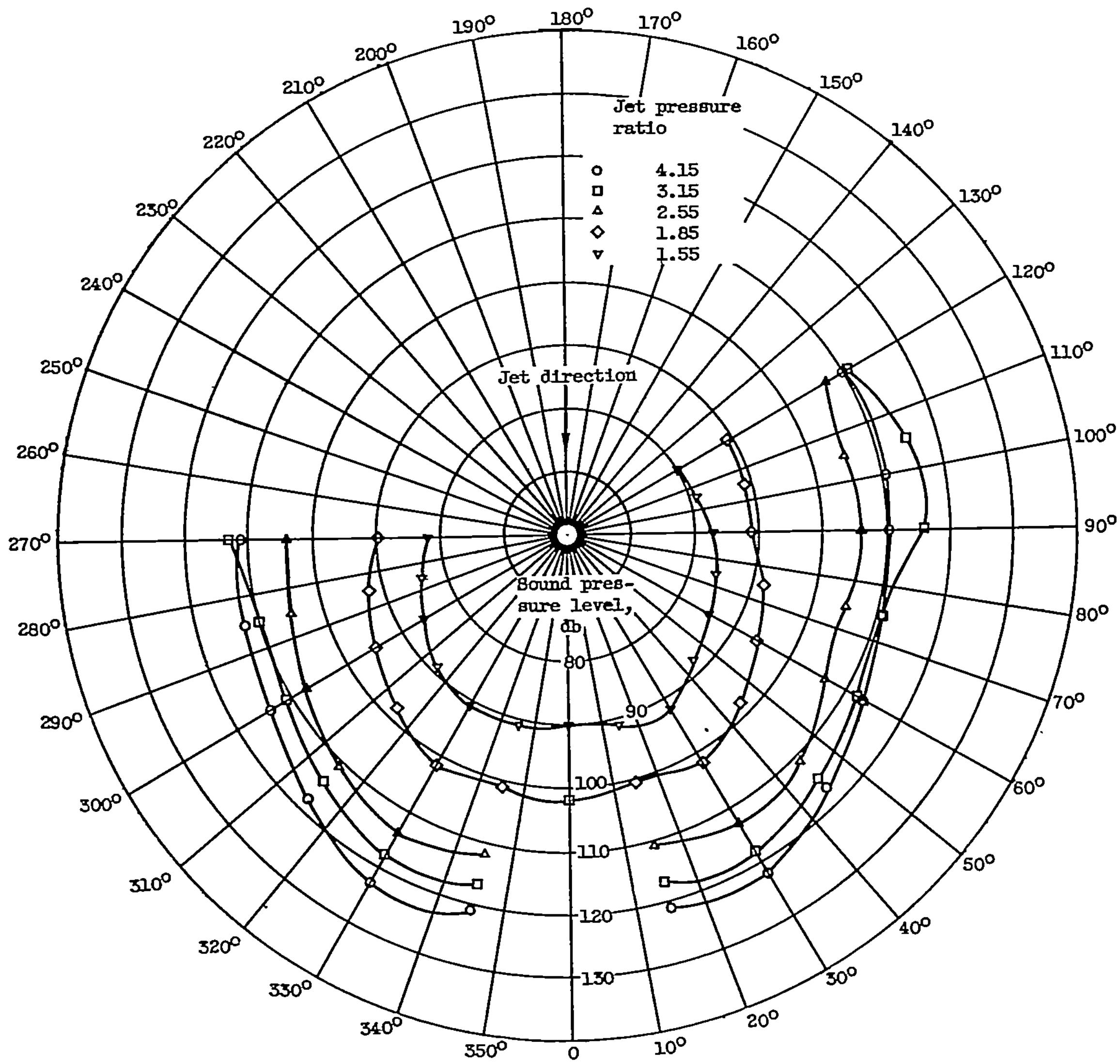
CC-6



(a) Conical plug; design pressure ratio, 4.0.

Figure 21. - Polar diagram of sound field for plug nozzles at various pressure ratios. Distance from jet exit, 50 feet.

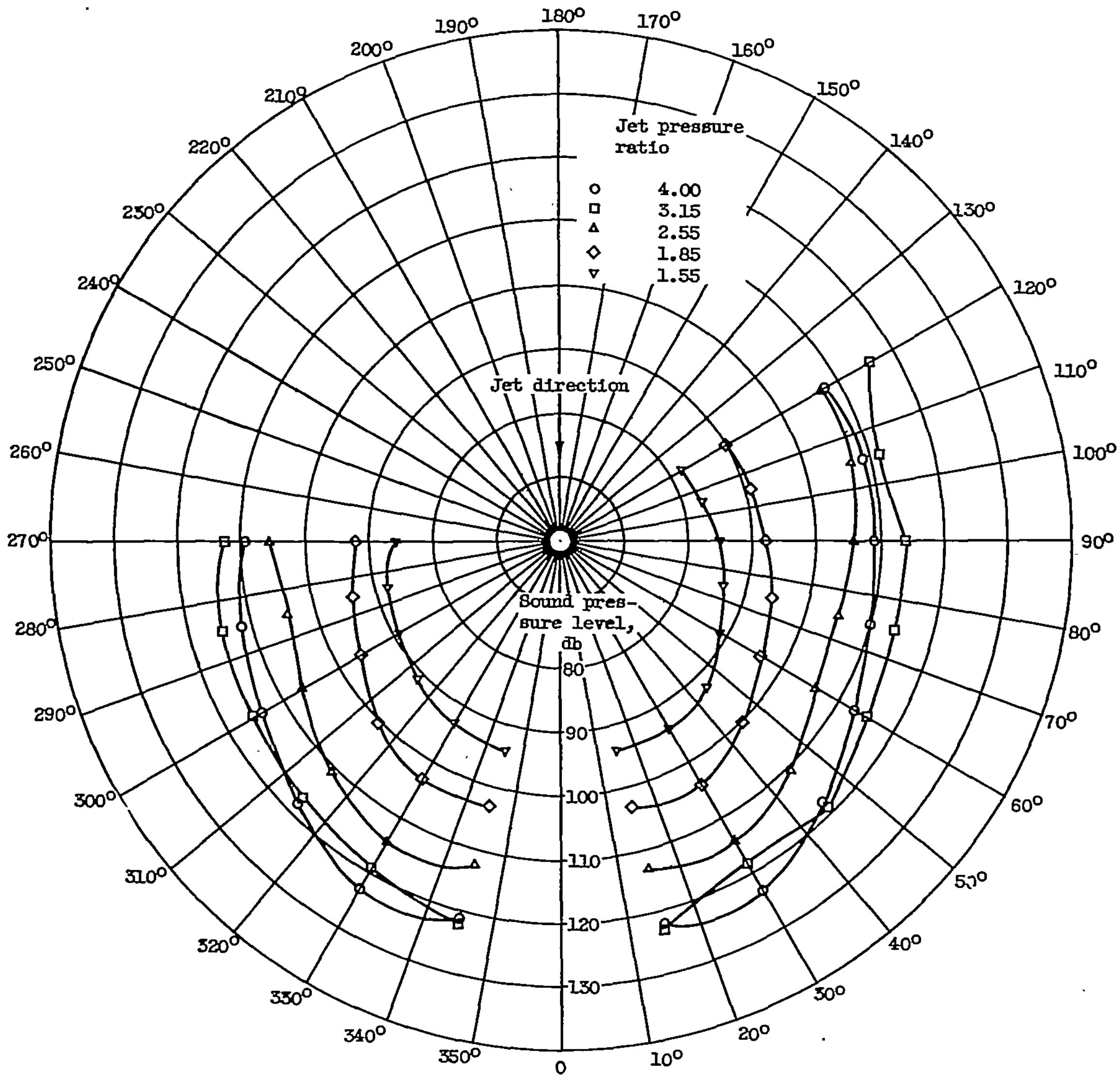


(b) Conical plug; design pressure ratio, 9.5.

Figure 21. - Continued. Polar diagram of sound field for plug nozzles at various pressure ratios. Distance from jet exit, 50 feet.

3838

CC-6 back



(c) Isentropic plug; design pressure ratio, 4.0.

Figure 21. - Continued. Polar diagram of sound field for plug nozzles at various pressure ratios. Distance from jet exit, 50 feet.

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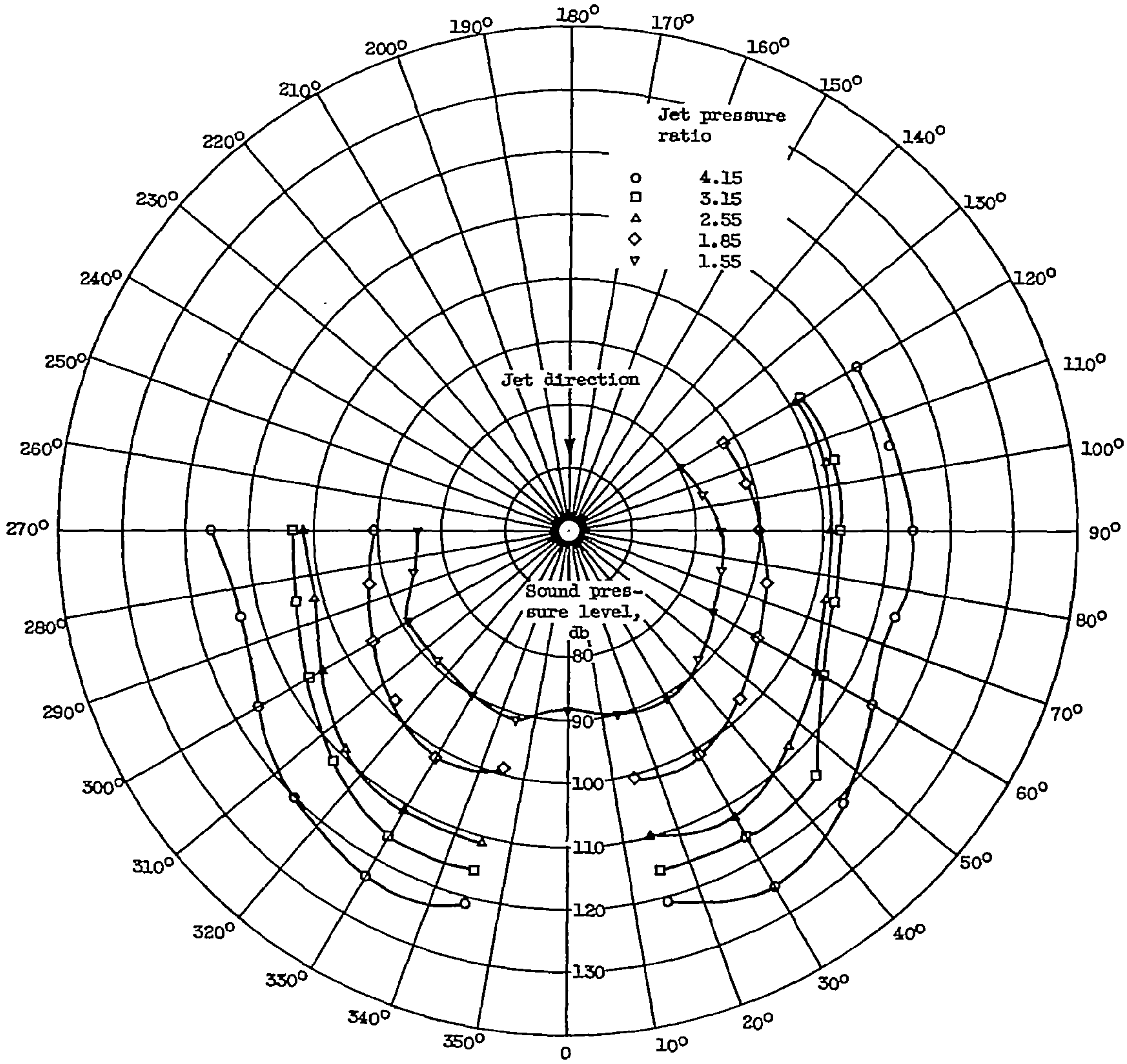

(d) Isentropic plug; design pressure ratio, 9.5

Figure 21. - Concluded. Polar diagram of sound field for plug nozzles at various pressure ratios. Distance from jet exit, 50 feet.